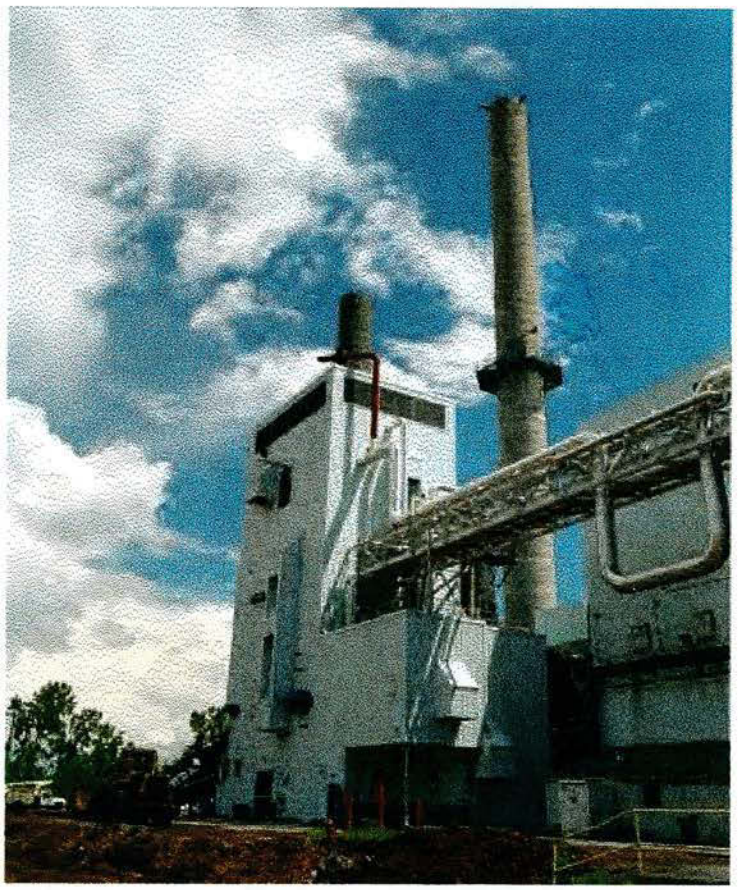
A SURVEY OF BIOMASS GASIFICATION 2001

Gasifier Projects and Manufacturers Around the World

2nd Edition

Thomas B. Reed & Siddhartha Gaur



The National Renewable Energy Laboratory
and
The Biomass Energy Foundation, Inc. Golden, CO. 80401

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The Database of Chapter 2 has been brought up to date with additions and corrections

Gasifier Projects and Manufacturers Around the World

Thomas B. Reed & Siddhartha Gaur

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Cover Picture: The 15 MW NREL/Battelle/FERCO gasifier located at the McNeil Power plant in Burlington, Vt. This plant uses a double circulating fluidized bed to produce medium energy gas. It became fully operational in August, 1999

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PREFACE TO THE 2001 EDITION

Why gasify biomass? While direct combustion of biomass produces heat, useful directly or in a boiler, gas can be used for cleaner and more controllable process heat, for driving engines or in turbines, fuel cells or Stirling engines for power, and for the synthesis of fuels and chemicals (such as methanol and ammonia). It is now becoming more competitive with fossil coal, gas and oil today; in other cases it will become so as the economical and environmental costs of fossil fuels rise. While coal gasification has long been practiced at a very large scale, only biomass can be used as a gasification fuel at small or large scale.

In 1979 one of the authors (TBR) published a "Survey of Biomass Gasification" for the Solar Energy Research Institute, SERI (now the National Renewable Energy Laboratory, NREL) [Reed, 1981]. At that time the only knowledge about biomass gasification was that in the World War II archives. Now, a great deal has happened in the field of Biomass Gasification and many gasifiers have been built and operated – and too often abandoned. This book is written to catalogue the gasification work to date with enough background to understand the difference between the many types of gasifiers. The National Renewable Energy Laboratory, NREL and the Biomass Energy Foundation, BEF, commissioned this book in an effort to make available new information on the current state of gasification.

During the year 2000 we sold a large number of books. We received some additions and corrections to the database. We have taken this opportunity to issue a 2nd edition and hope we can continue to do so each year. So, if you have additions or corrections to the database, please send them to reedtb2@cs.com.

We present an overview of the current state of Gasification Technology in **Chapter 1** in order to give the reader some perspective on the field and a minimum knowledge for purposes of navigation in this volume. There are thousands of gasifier systems in the world, many differing only in minor ways. We present in **Chapter 2** a summary of the gasifier manufacturers or projects that have we have found with extensive searching of the literature and in discussions with others. This list only skims the surface and gives no feel for the scope of each gasifier or project.

As a preparation for writing Volume I we (and others) have made site visits to a number of gasifiers and projects. These are reported in more detail for large gasifier system (>10MW) in **Chapter 3.** Small gasifier systems (<10 MW) and gasifier research establishments are discussed in detail in **Chapter 4**. **Chapter 5** reports on a number of organizations involved in gasification research. This is a rapidly changing field and we apologize here in advance to those working in a field that we may have slighted. We include in **Chapter 6** a conversion table between English and SI units; **Chapter 7** contains a brief glossary of technical words and acronyms; and **Chapter 8** contains a list of references.

I am pleased to announce that it is my perception that gasification is getting a great deal of renewed interest. This month it was announced that the long awaited Burlington/Battelle/FERCO gasifier had achieved continuous operation.

Thomas B. Reed January, 2001

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CHAPTER 1

1 CURRENT STATUS OF BIOMASS GASIFICATION

1.1 A SHORT HISTORY OF GASIFICATION

The fortunes of coal and biomass gasification have waxed and waned in a world rich in petroleum, coal and other fossil fuel reserves. The **classical age** of gasification (primarily coal) could be considered to extend from 1800 through 1940. By 1920 most cities in the world had a "gasworks" where **producer gas** (a mixture of primarily CO,CO_2, H_2, CH_4 and N_2 variously called city gas, town gas, manufactured gas, low Btu gas, LCG, ...) was made, stored in a gas holder, and delivered to the households and industries in town [Rambush, 1923]. With the development of long distance **natural gas pipelines**, this industry and all its knowledge disappeared. Now we need some of that knowledge again.

World War II was the **golden age** of biomass gasification. It was not practical to operate small gasifiers on coal, so most of the combatant countries relied on gas made from wood for civilian transport when the military commandeered the gasoline supplies [Egloff, 1943; NAS, 1985; GENGAS, 1979]. Over a million gasifiers were in use in Europe, an experience that suggests we could rely again on biomass gasification as petroleum runs out or threatens global climate changes.

In the first reaction to the oil embargoes of the 1970s many new gasification projects were ill conceived and were based on inappropriate coal technology. Most of these 1979 gasifier projects and manufacturers no longer exist for a variety of reasons. These were the **dark ages** of biomass gasification. However, some of these early projects have moved from planning to pilot testing to full scale to commercial. When the first "Survey of Biomass Gasification" was published in 1979 there were 81 projects and manufacturers of gasifiers reported.[Reed, 1981]. Of these, 49 responded to a questionnaire sent out and their one page responses were included in the book. Twenty of these projects were described in more detail by the authors. One of us (TBR) was the editor and a contributor to that book.

The "energy crisis" thinking of the period 1974-1984 has been tempered by the realization that the crisis was largely artificial and political and did not represent the imminent exhaustion of oil. The drop of oil prices in the mid 1980s caused the death of many projects based on the high price of oil. Since then however, there has arisen a global awareness of our role as stewards of Earth's resources and a fear that if we misuse them we will face climate changes and shortages that could end Civilization as we know it. This has caused a **Renaissance** in interest in biomass gasifiers as the best way of using renewable biomass energy. A recent article [Campbell, 1998] projects "The End of Cheap Oil", probably within 10 years. This could be a major boost to the interest in biomass gasification, but we have heard doomsday projections before, so must watch and wait.

During World War II, biomass gasification was used primarily for civilian transport in cars, trucks, boats and buses, but now gasification is seen primarily as a potential source of electric power: When used at a small scale it can bring the benefits of gas and power to the millions of villages around the world; at a large scale it can make biomass industries such as sugar and paper making independent of fossil fuels and fossil fuel prices.

We are glad in this volume to have the opportunity to bring the original list of gasifiers and projects up to date and evaluate the current state of world biomass gasification. In the second volume we will review the science and engineering of biomass gasification, but we give a minimum introduction here for our readers.

1.2 WHY GASIFY?

Wood and other forms of biomass (and coal) have been burned to produce heat as long as humans have existed. When gasification was developed about 1800, it was immediately apparent that gas was a superior, indeed necessary fuel for many uses. Although much of the world now burns natural gas (methane) today, for most of these 200 years "gas" has meant producer gas (city gas) made by gasification of coal or wood. **Producer gas** contains H_2, CH_4 and CO as the sources of energy and, typically some CO_2 and N_2 as unwanted diluents. If oxygen is used for gasification instead of air, a higher energy gas called "synthesis gas" is made. If gasification is performed with an external source of heat, a **pyrolysis gas** can be made with a much higher energy content.

Gasification might also be called "staged combustion", since usually the gas is produced from the coal or wood with intent to burn it later. So what is the advantage of first gasifying, then burning over just burning the coal or wood? The advantages are:

- Ease of distribution, in pipelines to whole cities or to each gas stove or lamp or cylinder in an engine
- Ease of control
- Continuous operation
- Clean combustion since impurities are removed in the gasifier (typically gas stoves and lights do not require external flues even for indoor combustion)
- Efficient combustion since one can mix gas with the correct amount of air for optimum combustion
- High temperature combustion for making glass or cement
- Intense combustion, increasing heat transfer an order of magnitude over coal and wood fires
- Power generation: While coal and wood can make steam for piston and turbine engines, these operate at relatively low efficiency and require large condensing areas. Gas can be used in spark, compression, turbine and Stirling engines for efficient power generation in compact units
- Chemical synthesis: Most nitrogen fertilizers and many other chemicals and synthetic fuels are made from synthesis gas - a mixture of hydrogen and carbon monoxide obtained from coal or wood by gasification or from methane by steam reforming

So, gas is useful for cooking, refrigeration (in gas refrigerators) and lighting (with mantle lamps), for process heat, for engine operation to produce work and power, and for chemical synthesis. The industrial revolution depends on having controllable fuels efficiently used. Gas fulfills that need and indeed it is hard to imagine the Industrial Revolution occurring without the easy availability of gas for heat, light and power.

1.3 WHY GASIFY BIOMASS

The first "energy crisis" brought to currency the word "**Biomass**" for wood and other forms of biomass when they are intended for supplying energy. The term includes wood, wood pellets (for pellet stoves), agricultural residues, energy crops and municipal solid waste, MSW. Biomass is a form of renewable energy and can potentially supply much of the Human energy needs forever (if we are careful to do it on a renewable basis and not too many Humans.) Recent concerns over increasing amounts of CO_2 in the atmosphere focus on renewable biomass use a "non-greenhouse" energy source, since the CO_2 is immediately recycled into the next generation of plants.

In addition, it is possible to make biomass gasifiers much smaller than coal gasifiers for use at a small scale for developing countries and isolated communities. Finally, various governments around the world offer special tax credits for biomass gasification, which is seen to be in the long range interests of the countries.

1.4 GASIFIER DEVELOPMENT ROUTES

There are thousands of gasifiers described in the patent literature and the literature of science and engineering. The combination of

- the various possible fuels
- the variety of sources and methods of delivery of heat
- the various methods of delivering air and fuel to the gasifier
- methods for gas cleanup and storage

makes possible many alternative routes to making gas. These various routes are intriguing to the inventor, entrepreneur, mechanical and chemical engineer. Speaking for myself (TBR), I find the number of ways this can be accomplished to be almost infinite, and infinitely fascinating. I am continuously astounded that I and others continue to develop new gasifiers after 200 years of gasifier development and use.

The general public and our officials also find gasifiers and gasification fascinating at times of energy shortage or environmental problems. It is then possible to obtain grants from government, Non Governmental Organizations (NGOs), benefactors and risk taking investors to finance gasification projects. This produces a rush of projects, many of which fail. Then gasification gets a had reputation and there is no money available for gasification. This goes in cycles, the memory of politicians and the general public being rather short.

Gasification of biomass lay dormant between the end of WWII and the first "energy crisis" (1974). There was then a great deal of funded work on gasifiers, much of which came to naught. In the mid-1980s the low cost of oil caused many of these to fail. Then in the 1990s environmental concerns have caused an upsurge of interest in gasification, which we hope will carry it to continuing commercial success.

Beware becoming interested in gasification unless you have tenacity and patience! **Expect** rewards for yourself and humanity when you succeed.

1.5 LARGE SCALE, SMALL SCALE, STOVE SCALE

Early "city gas" gasifiers were always developed at a **large scale**, since they required a distribution network to serve thousands of customers and could use coal, available at any scale required. Many of us remember the large gas holders on the horizon of most cities. City gas disappeared as natural gas pipelines spread across the country. During World War II small-scale gasifiers were developed using wood for emergency transport since the military commandeered all gasoline supplies for planes and tanks.

Current gasifier development focuses largely on heat and power. It is moving on three parallel tracks:

- Large gasifiers (> 10MW) for industries that have large concentrations of biomass fuels;
- Small gasifiers (<10 MW) for research, for developing countries, for small scale users with isolated heat and power requirements and access to biomass fuels.
- Very small gasifiers 2-4kW thermal for domestic cooking

While the principles of gasification are the same for all, the practitioners and funding sources are from two very different worlds, each only vaguely aware of the other. For this reason, we have separated the gasifier chapters into: large gasifiers (Chapter 3, >10 MWe, 50 MWth, 3 tons/hr) and the experimental units destined for large scale applications; and Chapter 4, small gasifiers (<10 MWe).

1.6 A FEW PRINCIPLES OF GASIFICATION

Ralph Waldo Emerson, American poet and essayist, said:

"Everything in Nature contains all the powers of Nature;

Everything is made of the same hidden stuff."

I take this to mean that the principles of gasification are universal, and only the practice varies. Once one really comprehends the principles, the practice will also become clear. If one does not understand the principles, we will continue to design gasifiers "by guess and by golly", and fads will come and go, maybe slowly homing in on the best solution, maybe not. It is planned to publish another volume on the science and engineering, principles and practice of gasification. We'll see.

1.6.1 A FORMULA FOR WOOD AND BIOMASS

In chemistry and engineering we do mass and energy balances by writing formulas such as

$$2H_2 + O_2 \rightarrow 2\,H_2O$$

Volume 2 1 2 (Volumes proportional to number of molecules or moles)

Wt: 4 32 36 (Weights proportional to molecular weights)

Unfortunately, while variations biomass has no exact formula, being composed primarily of varying amounts of cellulose, hemicellulose and lignin. The **ultimate analysis** typically gives the weight

% of C, H and O as well as S and N (minor) and ash and water. For instance an analysis might show **C: 52.2%; H: 6.1%; O: 41.7%** (weight basis). Dividing these by the molecular weights (C = 12; H = 1, O = 16) gives the relative number of molecules or moles, the mole fractions, (C = 0.333, H = 0.467, O = 0.20) or the mole percentages **C = 33.3%; H = 46.7%; O = 20%** (**mole basis**). Note that hydrogen is the highest fraction of biomass on a molecular basis, the lowest on a weight basis. Neither of these analyses are convenient to use in formulas. The MOLE RATIO formula, based on the ratio of H and O to C, gives a the workable formula for biomass that can be used in writing conventional equations,

$$\textbf{BIOMASS} = \mathbf{CH_{1.4}O_{0.6}}$$

This formula is an average for a large number of woods and other biomass species when the water and ash are subtracted from the organic material. Using this formula, it is possible to write chemical equations for the combustion, gasification and pyrolysis of biomass. The water and ash contained in the biomass typically are not altered during reaction, and so appear on both sides of equations. For very exact calculations it is desirable to have a more exact analysis, but, because biomass varies in detail, even the exact analysis only represents the fuel on a particular day.

1.6.2 A FORMULA FOR "AIR"

Air (at 0% relative humidity) is composed of approximately 21% oxygen (O_2) and 79% nitrogen (N_2). The air/O2 ratio is 100/21 = 4.76 by volume or 4.31 by weight. For every oxygen (O_2) consumed in our reactions, there will be 3.76 volumes of nitrogen (N_2) consumed. Since the nitrogen does not react, it appears on both sides of our equations. We can leave it out if we choose unless we are doing a mass or energy balance. This will be discussed in more detail in Volume II.

For a good discussion of the general principles of combustion and many detailed tables of data, see the North American Combustion Handbook, Vol 1 and 2 [NA, 1986, 1997].

1.6.3 PYROLYSIS, GASIFICATION AND COMBUSTION (PGC)

The relationships of three intertwined processes, **Pyrolysis, Gasification and Combustion,** shown schematically in Fig. 1, involved in biomass thermal conversion must be understood in order to put gasification in its proper perspective.

1.6.4 COMBUSTION OF BIOMASS

The eventual fate of most biomass that is pyrolysed and gasified is to be burned. (The exception would be manufacture of chemicals sucb as ammonia.) So we must understand the fundamentals of combustion even when our primary focus is gasification.

Most people believe that **wood burns.** However, if one looks closely at a burning match or fireplace, one sees that the pyrolysing wood does not burn at the wood surface; rather, the wood evolves a combustible gas, which burns wherever it meets the air. The visible combustion of the burning gas is called **flaming combustion** and is similar to the burning of a refinery flare or a candle or a match. If air is mixed with the combustible gases before combustion, as in a Bunsen burner, it is called a premixed flame; if air meets the combustible gases after they are generated, as in the matcb, it is called a diffusion flame.

Later, when the volatile materials in the wood have all burned, leaving charcoal, the charcoal appears to burn at its surface (although in fact it is burning by a complex process involving the formation of CO which burns very close to the surface). This process is **glowing combustion,** the process involved in the combustion of charcoal or coke.

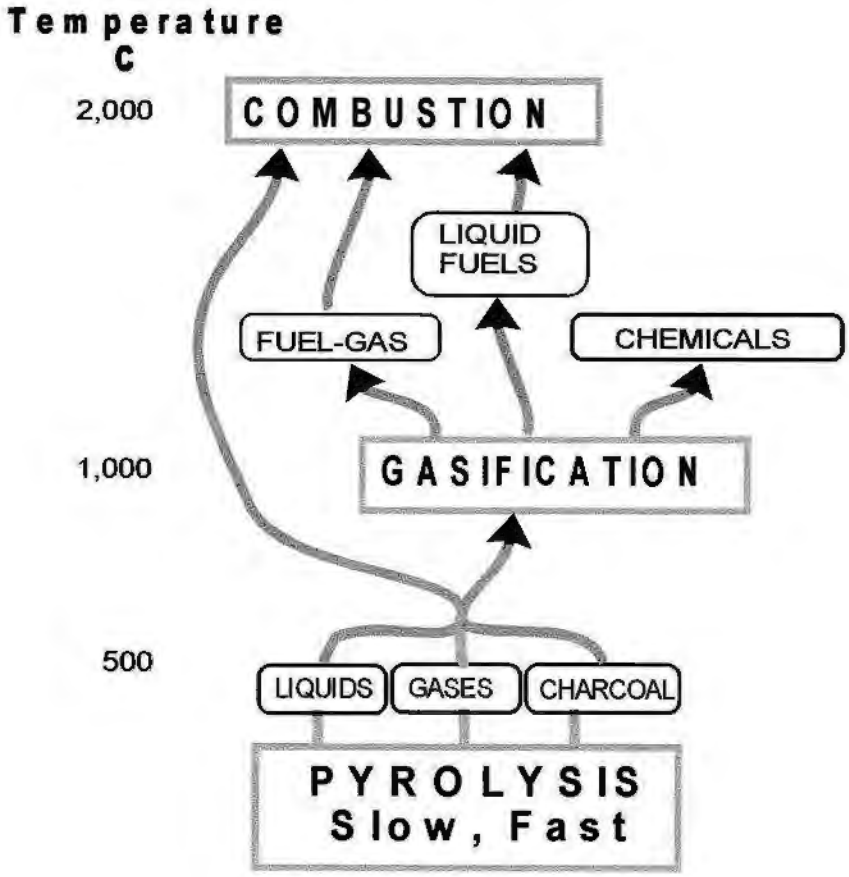

Fig. 1 - Pyrolysis (at 500 °C) yields liquid, gaseous and charcoal products which can be gasified (1,000°C) to yield a fuel gas, liquid fuels or chemicals; or the products (gases, vapors and charcoal can be burned directly for heat (2,000 °C).

The combustion of biomass can be represented by

$$CH_{1.4}O_{0.6} + 1.05\ O_2 \rightarrow CO_2 + 1.4\ H_2O$$

If air is used the reaction should be written

$$CH_{1.4}O_{0.6} + 1.05\ O_2 + 3.95\ N_2 \rightarrow CO_2 + 1.4\ H_2O + 3.95\ N_2$$

Combustion of biomass with air produces temperatures in the range 1,500 to 2,000°C in the combustion gases. Since biomass won't burn - only the gases from biomass burn - biomass combustion is ALWAYS preceded by pyrolysis and possibly gasification. While combustion is the end use of most gas from gasifiers, either as a gas or after conversion to liquid fuel, preliminary gasification has many advantages, as discussed below.

1.6.5 PYROLYSIS OF BIOMASS

Classically pyrolysis means the breaking down (lysis) of materials by heat (pyro) in the absence of air. In the case of the burning match however, the heat is subsequently produced by the burning gases; in a typical charcoal kiln some of the wood is burned to produce the heat to pyrolyse the rest. So, "absence of air" refers to the local process only.

In a pyrolysis kiln or a gasifier, biomass is subjected first to heat which releases gases and volatile materials according to

$$CH_{1.4}O_{0.6} \xrightarrow{\text{heat to } 500°C} \text{Gas} + \text{Vapor} + \text{Charcoal}$$

(The term **gas** here applies to gases which remain gases at temperatures below 0°C. The term **vapor** is reserved for liquid vapors that condense at temperatures as low as 0°C, ie water vapor, tar vapor etc.)

Figure 1 shows that pyrolysis underlies both combustion and gasification and that one can burn biomass vapors either directly after pyrolysis, or indirectly through preliminary gasification. Some scientists have spent their whole careers understanding any one of these fields and will admit that they do not fully understand even yet everything that occurs. Pyrolysis yields a residue of 10-25% charcoal. **Thus, in one sense pyrolysis is a partial gasification process.** Some gasifiers (ie, Battelle, Columbus) are designed around burning the charcoal separately to supply heat which is then recycled to the biomass to provide heat for pyrolysis.

The gases and vapors can be burned directly if hot; as they cool below about 400°C the vapors begin to condense and form "tars", a catchall phrase currently under much investigation. In pyrolytic gasification processes, the heat for pyrolysis can be supplied from external sources, but in air or oxygen gasification it is typically supplied by partial combustion of the charcoal or the gas/vapor. The "pyrolysis vapor" is typically 75-90% of the fuel mass. It consists of the fuel gases CO and H_2, CH_4 , the more complex volatile "tars" and some CO_2 and H_2O.

The resulting charcoal may be converted to gas by reaction with H_2O or CO_2, as described below. The charcoal produced has typically almost the same volume as the fuel, but contains 50% more energy on a weight basis. The pyrolysis process requires between 5 and 15% of the heat of combustion of the wood (dry basis) to raise the wood to pyrolysis temperature and vaporize the products. This is a temporary investment in the charcoal and combustible gases that will be paid back with 1000% interest on combustion of the final products. (Heat of pyrolysis ~ 2 kJ/g; heat of combustion ~ 20 kJ/g).

"Fast" Pyrolysis has been developed in the last decade as a method of producing a **liquid** pyrolysis oil, "biosyn" or "biocrude", from biomass with yields of 60-75% liquid. Very high heating rates are used at 450-550°C with small particles. Very little gas is produced, so fast pyrolysis is an alternative to gasification, a whole other field [Bridgwater, 1995]. At higher temperatures (>700°C) the pyrolysis liquids are further cracked to gases and this has been used for generating medium energy gas. This is the basis of **pyrolytic gasification.**

1.6.6 GASIFICATION OF CHARCOAL AND COKE

Charcoal Gasification processes occur at temperatures of 700 to 1200°C. They must ALWAYS be preceded by pyrolysis, since one can't reach these temperatures without passing through the pyrolysis range.

In the days of coal gasification "gasification" was almost exclusively used to indicate the processes involved in converting charcoal (from wood) or coke (from coal) to CO and H. These reactions are

$C + CO_2 \rightarrow 2\,CO$ The Boudouard Reaction

$C + H_2O \rightarrow CO + H_2$ The Water Gas Reaction

Beware of most early explanations of biomass gasification that give these as the primary reactions! True for coal; false for biomass, since at most only 1/3 of the biomass is converted to charcoal during the pyrolysis step.

It is much easier to gasify charcoal than biomass, since there are no volatile "tars" formed. Gasifiers at the beginning of WW II used charcoal. However, manufacture of charcoal wastes 2/3 of the energy in biomass, so there is a strong incentive to use biomass rather than charcoal.

1.6.7 GASIFICATION OF BIOMASS

Biomass pyrolysis produces typically 75% to 90% volatile material, so that converting the volatile materials to gas is the major task in biomass gasification. This would be represented by for instance

$$CH_{1.4}O_{0.6} + 0.35\,O_2 \rightarrow 0.4CO + 0.6H_2 + 0.4CO_2 + 0.1H_2O + \mathbf{0.2C}$$

if thermodynamic equilibrium was reached. However, the temperature of the above reaction is low enough so that much of the product appears as liquid vapors. In updraft gasifiers the remaining carbon is burned to generate heat for pyrolysis. In downdraft gasifiers some of the remaining carbon is converted to CO and H_2 by the Boudouard and water gas reactions above. In fludized bed and entrained gasifiers all of these reactions happen simultaneously.

1.7 FIXED BED GASIFIERS

The common names of gasifiers (updraft, downdraft, fluidized hed, entrained flow) reflect the way the fuels flow and are supported and simultaneously the way the air/oxygen flows to the fuels. Use of these names helps in reading the literature on gasifiers, but actually hinders understanding the operation of newer gasifiers. We will follow the practice here of using the common name with important reservations in the discussion.

It would be possible to include pictures of hundreds of gasifiers here. Rather, in this chapter we will list the **principal** gasifier types. We will include diagrams of many specific gasifiers in the discussions of Chapters 3 and 4. We will apply the above principles in Volume II to detailed operation and modelling of gasifiers.

In the gasification process heat can be supplied by direct combustion of the pyrolysis gases (flaming pyrolysis in downdraft or co-flow gasifiers) or by combustion of the charcoal separately (updraft gasifiers), or by a combination (fluidized beds).

Every gasifier and combustion device employs some form of heat recycling to generate the 5-15% heat required for pyrolysis, as shown in Table 1. Arranging to have this heat delivered to the incoming fuel is the principal prohlem in gasifier design and accounts for the wide varieties of gasifiers.

Table 1 - Sources of Heat for Gasification in Various Types of Gasifiers

TYPE OF GASIFIER	SOURCE OF HEAT FOR PROCESS
Updraft	Combustion of Charcoal
Downdraft	Partial combustion of Volatiles
Fludized Bed	Partial combustion of Volatiles and Charcoal
Entrained Flow	Partial combustion of Volatiles and Charcoal
Pyrolytic	External – (charcoal, tar, propane…)

1.7.1 The UPDRAFT (*COUNTERFLOW*)

The distinction of **updraft** and **downdraft** sounds trivial. Yet they are profoundly different processes. The figures are worth close study.

The **UPDRAFT** (*counterflow, char burning*) gasifier (Fig. 2) is the oldest and simplest form of gasifier and is still widely used for coal gasification (Lurgi). Counterflow refers to the fact that fuel is introduced at the top (through a star valve or lock hopper) and flows down, while air/oxygen (and often steam or CO_2) are introduced below a grate on which the charcoal produced by pyrolysis sits. The gases flow up as shown in Fig. 2. The first few layers of charcoal burn fiercely to produce hot CO_2 and H_2O which are then reduced in part to CO and H_2 as they pass up through the balance of the descending charcoal with cooling to about 750°C in the charcoal gasification reactions above. (For this reason "char-burning" is a more general term for this type of gasifier). Continuing up, these hot, reducing gases pyrolyse the descending dry biomass and finally dry the incoming wet biomass and pass out at a low temperature. From top to bottom (following the fuel flow) the processes are:

1) **Downflowing** fuel is dried by **upflowing** hot gases with good heat recovery
2) Downflowing dry fuel is then pyrolysed by t4he upflowing gasification gases, producing prompt gas/vapor and charcoal and recovering their heat
3) Downflowing charcoal at 800-1200C reacts with the upflowing CO_2 and H_2O resulting from charcoal combustion in (4) to produce CO and H_2
4) Downflowing charcoal burns with entering air/oxygen/steam/CO_2 at the grate at very high temperatures
5) Downflowing ash falls to ash disposal

The composition and temperature at each point in the gasifier is somewhat diagrammatic, since much more would need to be specified about fuel, oxidant and reactor conditions to make them specific. Still, they portray the history of the gases and solids as they pass through the gasifier.

The **advantages** of the updraft (*counterflow*) gasifier are

- Simplicity and the ability to gasify materials with high water and inorganic content, such as MSW
- Potentially high grate temperatures (unless steam is injected with air) capable of melting metals and minerals (slagging gasification)

. The **disadvantages** are

- The gas will contain 10-20% tar resulting from the pyrolysis reaction. These tars burn well in direct combustion.
- The tar needs to be removed for any engine, turbine or synthesis applications.
- The grate can be subjected to very high temperatures unless the incoming air/oxygen is moderated with steam or CO_2.to soak up excess heat.
- All producer gas is hazardous, containing CO

The **updraft** ***counterflow*** gasifier is occasionally used for biomass in situations involving high ash (MSW) or where the tars don't need to be removed for subsequent combustion. The Purox and Andco Torrax (Caligua) gasifiers were "slagging" updraft gasifiers [Patent, 1973; Purox, 1979;Sofresid, 19]; the Wellman Co. in England now makes an updraft gasifier for engine operation [IEA, 1996].

1.7.2 THE DOWNDRAFT (*CO-FLOW*) GASIFIER

The **DOWNDRAFT** (***co-flow, tar burning,*** *also called* Imbert, Stove, Stratified Downdraft, topless, open core, etc.) gasifier, Fig. 3, looks much like the updraft (*counterflow*) gasifier in its essentials and is often mechanically similar, except that the air and gas flow down, in the same direction as the fuel. This makes ALL the difference with a high volatile fuel such as biomass. The incoming air/oxygen cam burn more than 99.9% of the tars. (Therefore a more generic name is "**tar burning**".) Since the incoming air meets the unburned biomass first, the highest temperatures occur only in the gas (not the solids) in the pyrolysis region as shown in Fig. 3. (Again, the composition and temperature at each point in the gasifier is somewhat diagrammatic, since much more would need to be specified about fuel, oxidant and reactor conditions to make them specific. Still, they portray the history of the gases and solids as they pass through the gasifier.)

The steps are:

1) Downflowing fuel (<20% MC) and air/oxygen approach the reaction zone and are ignited
2) The flame generates pyrolysis gas/vapor which burns intensely around each particle until the volatiles are exhausted, leaving 5-15% charcoal.
3) Downflowing rich combustion gases from (2) react with the charcoal at 800-1200C generating more CO and H_2 and reducing gas temperature below 800°C.
4) Downflowing char ash (typically 4-8%), too cool to react, passes out through the grate to char/ash disposal.

The **advantages** of the downdraft (*co-flow*) gasifier are:

1) It consumes between 99% and 99.9% of the tar and so the gas can be piped or used in engines with minimal tar cleanup.

2) The minerals remain in a matrix of unconverted char-ash, greatly reducing the need for a cyclone or hot filter
3) The downdraft is a proven system with over a million vehicles operated during WWII
4) The downdraft gasifiers are very simple to make and can be built in any small shop equipped for welding and piping with mild steel
5) The gas (when clean) can be used in existing engines without major modification

The **disadvantages** are:

1) The fuel should have a low moisture content, (< 20%)
2) The gas emerges from the gasifier at 700°C and the heat must either be wasted or recovered (fuel drying, input air heating ...)
3) Typically 4-7% of the carbon is unconverted
4) Spark engine peak power is reduced 30-40% unless supercharged
5) All producer gas is hazardous, containing CO

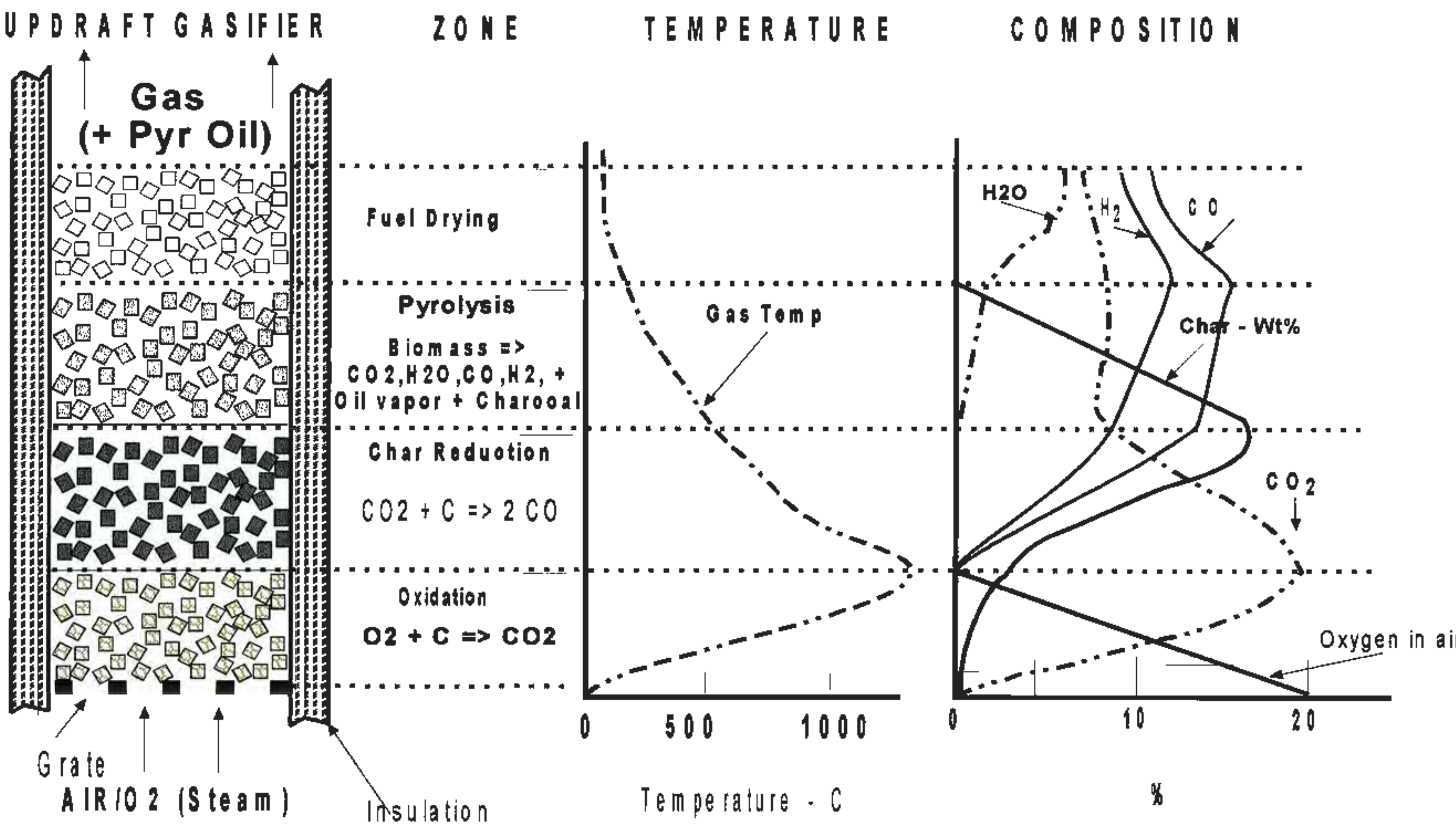

Fig. 2- Schematic diagram of an updraft gasifier showing the gasifier zones, the reactions, the temperatures and the gas composition (zone height not necessarily to scale). Air or oxygen passes up through a grate and burns charcoal, generating very high temperature CO_2 in the oxidation zone; the CO_2 is then reduced to CO (endothermic, gas cools) in the reduction zone; the hot gas then pyrolyses and dries the incoming fuels.

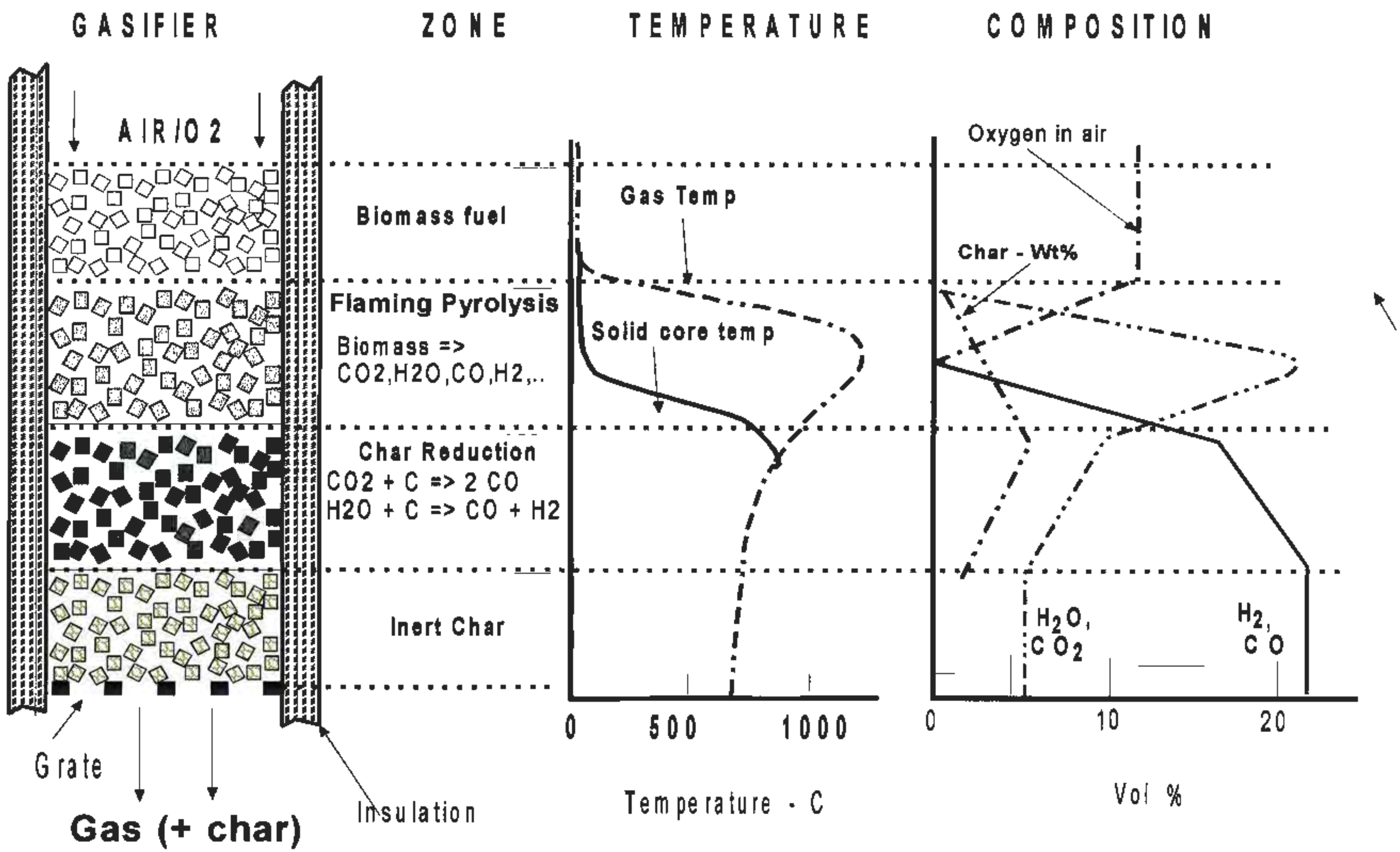

Fig. 3 - Schematic diagram of a (stratified) downdraft gasifier showing the gasifier zones, the reactions, the temperatures and the gas composition (zone height n ot necessarily to scale). Air or oxygen entering from above encounters burning wood in the flaming pyrolysis zone where most of the volatiles are initially burned to CO_2 and H_2O and then as oxyen is consumed, to CO and H2; when pyrolysis is complete CO_2 and H_2O are reduced by the charcoal.

1.7.3 The CROSSDRAFT GASIFIER

The crossdraft gasifier is of mixed parentage and so is more difficult to understand, model and use. It is the simplest and lightest gasifier. Air enters near the bottom of a cylindrical container at high velocity inducing substantial circulation, as shown in Fig. 4. It flows across the bed of fuel and char. The gas exits at the opposite side. The unused fuel occupies most of the container. Fuel and ash insulate the walls of the container, permitting use of mild-steel for all partes except the nozzles and grates which may require refractory alloys or some cooling. The high temperature reached requires a low ash fuel to prevent slagging [Kaupp, 1984].

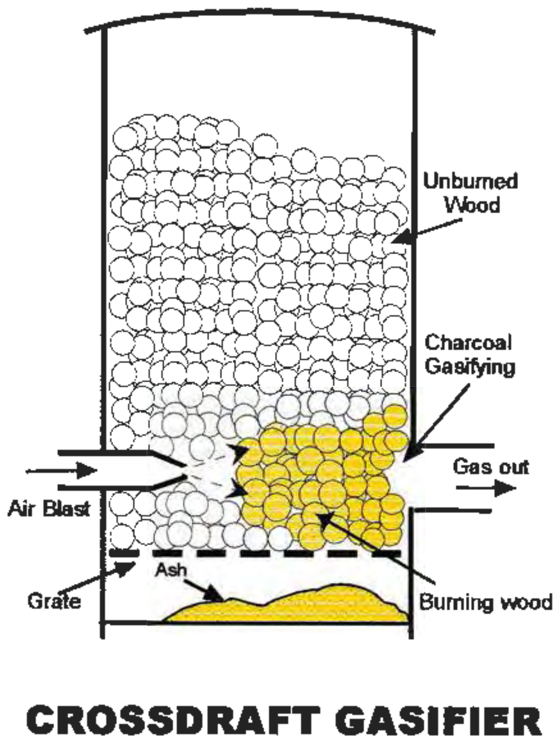

Fig. 4- Diagram of crossdraft gasifier

1.8 FLUID BED AND ENTRAINED GASIFIERS

1.8.1 Fluidization and Entrainment of solid particles by flowing gas

Material handling of solid fuels is a major mechanical problem in gasification. If increasing amounts of gas are passed up through a bed of material, it is obvious that eventually the force of the gas will overcome the weight of material and levitate the solids. In fact, when the product of the pressure drop across the bed and the bed area is equal to or larger than the weight of the bed, the bed expands and all the particles begin moving, some up, some down. The various stages of levitation are shown in Fig. 5. Fig. 6 shows the configuration for a fluidized bed gasifier along with a temperature profile and possible gas distribution. For reasons of stability, the pressure drop in the injectors must be greater than that in the bed.

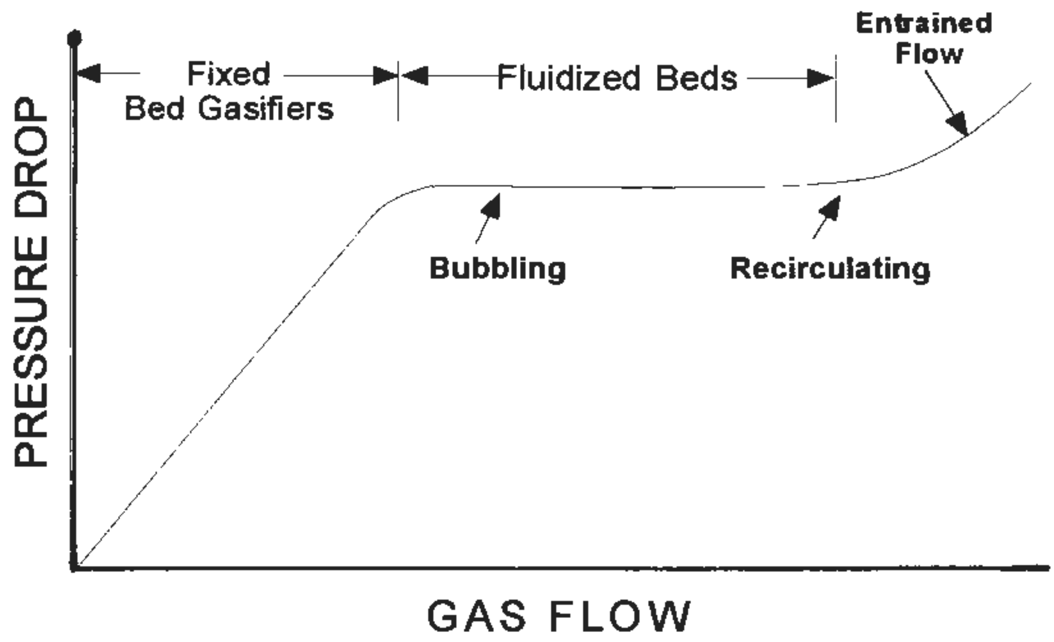

Fig. 5 Fixed and Fluidized Bed flow regimes for gasifiers

1.8.2 Fluidized Bed Gasifiers

The fluidized bed (FB) was developed before World War II for large coal gasification systems (Winkler). It was then adopted by the petroleum and chemical industry for cracking heavy hydrocarbons, catalysis, drying and a thousand other uses. (My oculist uses a sand fluidized bed to soften my glass frames for bending). Fluidized beds are noted for having high throughput rates and high heat transfer rates. They are more complicated to operate than fixed beds and so tend to be used in larger installations.

Fluidized bed combustors (FBCs) have been very successful in the combustion of biomass and over 50 are operating in California alone in the 10-50 MWe size range.

When biomass gasification became attractive in the 1970s, it was natural to use fluidized beds for larger systems. In some cases the fuel itself forms the bed of the gasifier; in other cases an inert material such as sand, dolomite or alumina forms the bed and acts as a heat transfer agent for the fuel materials passing through the bed. A typical temperature profile and hypothetical gas composition for a bubbling fluidized bed gasifier is shown in Fig. 6. Actual temperatures are almost meaningless in the bed in the presence of high heat transfer rates where the bed material, biomass and gas are at very different temperature. In addition, the gas composition varies continuously around each particle.

Fluidized bed gasifiers are discussed in most of the books in the bibliography. Of particular help is a book on "Fluidized Bed Combustion and Gasification: A Guide for Biomass Waste Generators" prepared by FBT, Inc. [FBT, 1994].

The fluidized bed has the highest throughput of the various gasifier types for a given cross section, although other gasifiers may have a higher throughput on a unit volume (see below). Fluidized bed gasifiers have a wider range of fuel flexibility than other fixed bed types, but they should not be characterized as being able to utilize "any fuel". The maximum dimension of particles is typically 5-10 cm. Fluidized beds also have a higher tolerance for moisture and can operate with as high as 65% water content in the fuel. However, it is wise to reduce moisture content as low as practical for process efficiency. (Use waste heat, not process heat for drying.) Biomass fuels for **FBGs** should have an ash softening temperature greater than the FBG operating temperature to minimize agglomeration.

Fluidized bed gasifiers come in a wide variety of forms, depending on the degree and manner of levitation, the particle size being used and the end use of the gas. At the lowest end of the range (Fig. 5) they are "incipiently fluidized" or levitated. The bed is quite homogeneous, but throughput is low. At somewhat higher flows, they are called "bubbling fluidized bed gasifiers" (BFBG) and bubbles of gas pass through the solids with less contact with the solids. At the highest rates some of the fluidizing material is carried out with the gas and is separated by a cyclone and returned to the bottom of the bed in the "recirculating fluidized bed" gasifiers (RFBG). There are many ingenious designs of fluidized beds, including the two fluid bed of the Battelle process. The details are discussed specifically for each gasifier in Chapter 3.

Operation at more than a few percent over atmospheric pressure is very difficult and requires lock hoppers or pressure screws or compactors and special seals. However, there are many advantages to pressurized fluid bed gasifiers (PFBGs) operating at 10-20 Bar. Gas turbines typically use high-pressure gas fuels. The throughput of the gasifier increases rapidly (approximately 0.6 power) with pressure. Gas filtering with ceramic candles is only economically justified in high-pressure gasifiers. High pressure is usually required for chemical synthesis, so high-pressure operation increases efficiency of producing fuels and chemicals significantly.

1.8.3 ENTRAINED FLOW GASIFIERS

At the highest high flow rates shown in Fig. 5 all the particles are carried over in one pass. This type of gasifier is only useful for very small particles and liquid droplets. The Texaco Corporation has used this type gasifier for liquids and coal.

1.9 PYROLYTIC GASIFIERS

As mentioned previously, conventional pyrolysis produces a mixture of 1/3 charcoal, 1/3 gas and 1/3 pyrolysis oil. As heat transfer rates go up, however, as much as 70% of the biomass can be converted to an oxygenated oil, composed of the monomers and fragments of the components of the biomass (cellulose, hemicellulose and lignin and, for RDF, plastics) provided the volatiles stay under about 600°C. If the volatile materials reach >800°C, they are largely cracked to a gas containing ethylene and other hydrocarbons.

This forms the basis of several gasification processes discussed in Chapter 3; the Battelle two fluid bed gasifier and the Thermochem/MTCI pulsed combustor steam gasification process.

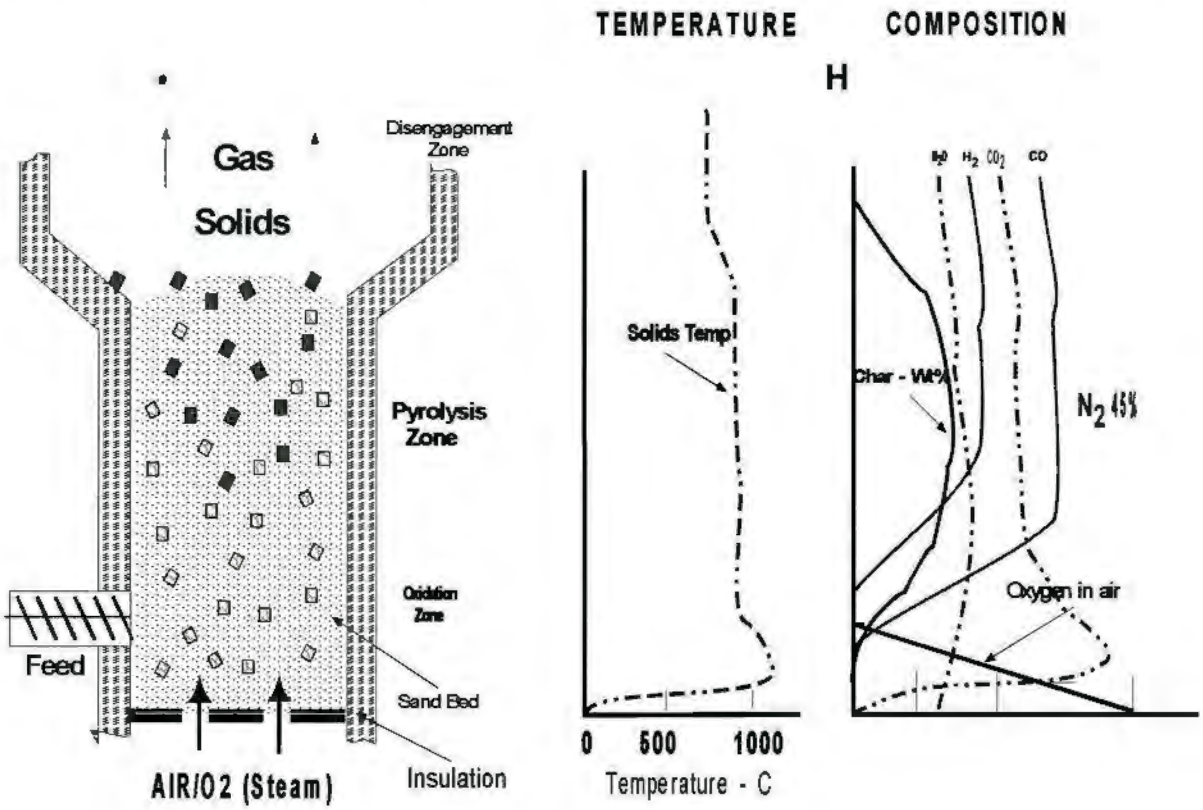

Figure 6 - Schematic diagram of a fluidized bed gasifier

1.10 GASIFIER SCIENCE

Gasifier science will be covered in detail in Volume II, but a few key subjects will be mentioned here.

1.10.1 The Air/Fuel Equivalance ratio

One of the most fundamental parameters in combustion and gasification is the air-fuel equivalence ratio, ϕ defined as

ϕ = Air (or oxygen) used in process/Air required for complete (Stoichiometric) combustion

Typically, it requires 6.26 kg of air to burn 1 kg of dry wood, since (144.1/23 = 6.26) [Desrosiers, 1979]

MOLES: $CH_{1.4}O_{0.6} + 1.05\ (O_2 + 3.76N_2) \rightarrow CO_2 + 0.7\ H_2O + 3.95\ N_2$

MASS: 23 144.1 44 12.6 110.5

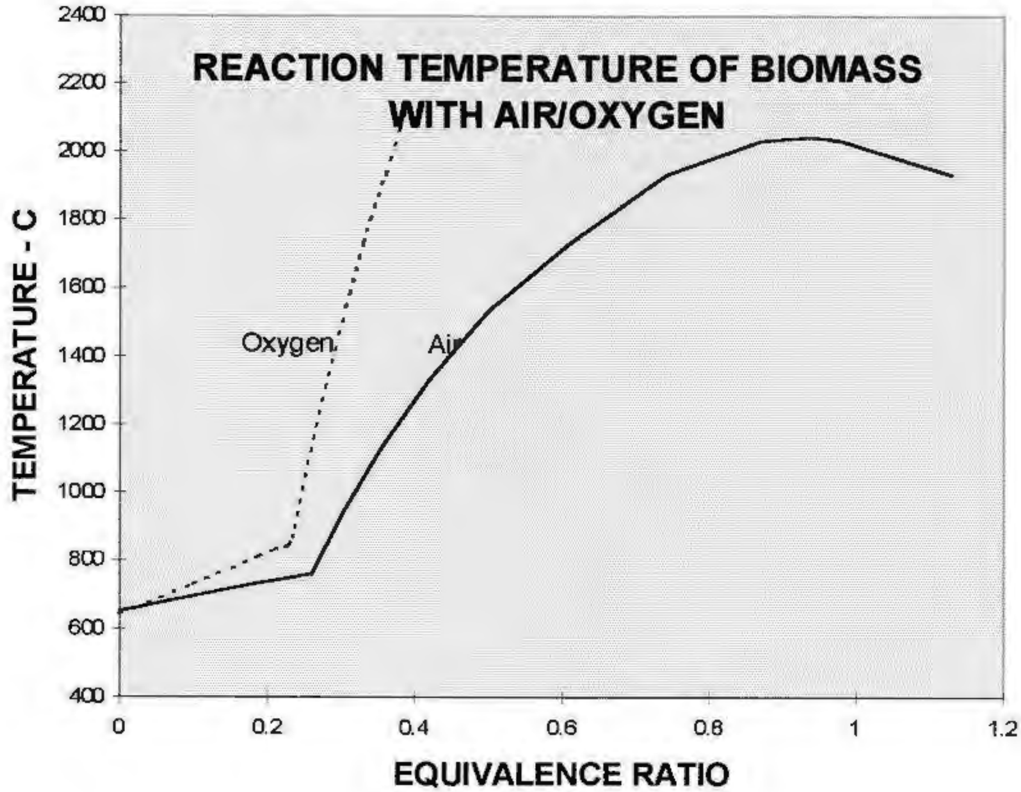

Fig. 7 - Temperature of the reaction of dry biomass with air or oxygen as a function of equivalence ratio

Thermodynamic calculations show that at equilibrium this same wood can be converted to gas using only about 1.56 kg of air. The relationship between temperature and air/oxygen consumed is shown in Fig. 7. Detailed calculations of various biomass reactions and the results of thermodynamic calculations were discussed in the first Survey [Reed, 1981].

This single figure explains a lot about **pyrolysis, combustion** and **gasification**. The equilibrium reaction temperature for **complete combustion** of wood is about 2100°C, not very different from that of natural gas or hydrocarbon fuels. Surprisingly (to me) the equilibrium temperature for **auto-pyrolysis** (pyrolysis without external heat input or air, $\phi = 0$ in Fig. 7) is 550°C. (This is an artificial concept, since normally pyrolysis does not yield equilibrium mixtures of gases and charcoal because the temperature is too low.) The equilibrium reaction temperature for **complete gasification** is 725°C and this temperature and the gas composition corresponds quite closely to that of the gases as they exit a downdraft gasifier where the conditions are close to ideal for achieving equilibrium. (Methane tends to be higher than shown by equilibrium calculations.) Note that as the equivalence ratio increases beyond 0.25, the gas temperature rises rapidly. This is the operating zone of fluidized bed gasifiers.

1.10.2 Thermodynamics of Gasification

Thermodynamics predicts the end products of a reaction, provided sufficient time is available for the reaction to go to completion. Most chemical reactions reach equilibrium in a fraction of a second at temperatures over 1000°C. An extended set of calculations are available that show the effect of moisture, pressure and oxygen content on the gas and char output [Reed, 1982].

1.10.3 Kinetics of Gasification

At lower temperatures (<500°C) reactions may take hours or never proceed. Catalysts can promote these reactions at lower temperatures. The application of thermodynamics and kinetics to biomass reactions were discussed in the first Survey [Reed, 1982].

1.10.4 Comparison of Gasifiers using "Figures of Merit"

While we often have data specific to particular gasifiers, it is quite difficult to compare performance between different types and sizes and manufacturers. There are a number of "figures of merit" that reduce data from various gasifiers to a common denominator so that one can compare gasifiers that are widely different in scale and type. (The listing of "price per kg" of various products in the supermarket makes it possible to determine unit costs without carrying a computer to the store; "dollars per square foot" is often used to compare the cost of homes and other real estate.)

The Superficial Gas Velocity, SGV (Area Thruput), a Fundamental Parameter

The **superficial gas velocity** (SGV) is an important quantity that is easily calculated from the most basic information on gasifiers, i.e.

$$SGV = \text{Gas production } (m^3/sec)/\text{Internal Cross Section Area } (m^2) \rightarrow \text{velocity } (m/sec)$$

The word "superficial" refers to the fact that the SGV is not actually a velocity, but has the units of velocity as shown above. It is based on the gas production measured at normal temperature and pressure (not at gasifier temperature) and uses the gasifier internal diameter without reference to internal fuel or equipment which would cause the real velocity to be higher. It might be more properly called the "area thruput", but we will use the historic term here.

The superficial velocity has long been used to compare widely different gasifiers. Many other factors are easily derived from this number or used to derive this number. In addition, the SGV has a major influence on the conditions and products of gasification and this influence will be discussed in Volume II.

The following table (2) illustrates comparison of the SGV of a number of gasifiers.

Table 2 - Maximum Reported Superficial Gas Velocity of Various Gasifiers

GASIFIER	TYPE	ID	AREA	MAX FLOW	SV
		m	m^2	m^3/sec	m^3/m^2-sec
Imbert	Nozzle Downdraft	0.30	0.071	0.045	0.63
SERI Air	Stratified Downdraft	0.15	0.018	0.005	0.28
SERI Oxygen	Stratified Downdraft	0.15	0.018	0.004	0.24
Syn-Gas – Air	Stratified Downdraft	0.76	0.454	0.776	1.71
Syn-Gas – Oxygen	Stratified Downdraft	0.76	0.454	0.485	1.07
Buck Rogers	Stratified Downdraft	0.61	0.292	0.126	0.43

Notes: From [Reed, 1988]; Imbert gasifier measured at ID, not constriction. Buck Rogers from [Chern, 1985].

Notes: From [Reed, 1988]; Imbert gasifier measured at ID, not constriction. Buck Rogers from [Chern, 1985].

The SERI pilot gasifier had the lowest thruput, while it's offspring, the Syn-Gas gasifier had the highest (due to its enclosed refractory top). None of these relations would be evident from the raw data, and were not evident at the time of operation.

THERMAL POWER: If one knows the heating value of the gas (HV), the thermal thruput is calculated from

$$P\,(th) = HV \times SGV$$

The air gasifiers listed above typically have a heating value of 5 MW/m^3. The oxygen gasifiers produce a gas with a heating value of 10 MW/m^3. These give the power thruputs shown in Table 3.

Table 3 – Relation of Heat, Power, Fuel Velocity and Gas production to SGV

Gasifier	Superficial Velocity	Heat Power[1]	Electric Power[2]	Fuel Velocity[3]	Superficial gas Production
	m^3/m^2-s	MWth(1)	MWe	mm/sec	m3/m^2-hr
Imbert	0.6	3.2	0.95	0.5	84
Buck Rogers	0.4	2.2	0.65	0.3	57
SERI Air	0.3	1.4	0.42	0.2	37
SERI Oxygen	0.2	1.2	0.36	0.2	32
Syn-Gas – Air	1.7	8.6	2.57	1.2	228
Syn-Gas – Oxygen	1.1	5.4	1.61	0.8	143

Notes: [1] – gas heat content 5 MJ/m^3; [2] – efficiency 30%; – particle size 3 cm

ELECTRIC POWER:

If the efficiency [ε (p)] of power generation using the gas is known, the power thruput is given by

$$P(e) = \varepsilon\,(p) \times HV \times SV$$

and values for the gasifiers above are shown in Table 3.

FUEL VELOCITY (FV):

If one knows the bulk density of the fuel, ρ (typically 200 kg/m^3 for wood chips), the heating value of the fuel (typically 18 GJ/m^3), tbe efficiency of gasification (typically 0.7) and the beating value of tbe fuel one can calculate the velocity of fuel flow at steady state in the gasifier from the energy balance as

$$FV = \rho \times e\,(g) \times SGV \times HG/HF$$

These velocities are shown in Table 3. (They are shown in mm/sec because they are so small relative to the gas velocities. Multiply by 3.6 to get m/hr.)

SGV Relationships

Significance of SGV and SGP:

While the SGV is a measure of how big the "footprint" of the gasifier will be (cross section area), the SGP is a measure of the volume occupied, and the relative mass and construction cost. It is also inversely proportional to heat loss. The SGV of a fluidized bed is typically higher than for fixed bed gasifiers because of the excellent heat transfer in the bed. However, fixed bed gasifiers typically bave higher gas production per unit volume as shown by the SGP figures above.

Gas Production (SGP):

While superficial gas velocity is a measure of gas production per unit cross section, the superficial gas production is a measure of production rate per unit volume, where h is the active bed height of the of the gasifier (where heat losses occur and insulation is required).

$$SGP = \text{Gas volume per sec/gasifier volume} = SGV/ h\times A \ (m^3 gas/m^3 vessel\text{-}sec)$$

It is seen in Table 3 that gasifiers produce gas flows equal to 30-200 times their volume. This is a very high specific reaction rate. The active zone of the gasifier required to operate a 50-hp car engine is smaller than the engine itself (the actual gasifier is much larger, but includes the fuel (tank) magazine. (As a reference, biogas digesters typically produce 1 m^3 of gas/m^3 of vessel per hour from manure. We once calculated the methane production from cow stomachs as 7 m^3 gas/m^3 stomach-hr.)

In fluidized beds, the active zone only depends on the vessel dimensions. In fixed bed gasifiers, the height of the active bed is difficult to determine, and depends particularly on fuel size and moisture content. These will be discussed in more detail in Volume II. For now the 3-6-9 rule illustrates the calculation. Typically the flaming combustion zone is 3 particle diameters in depth and the char gasification zone is 6 particle diameters in depth, yielding an active zone 9 particle diameters in depth. The active zone for a 3 cm particle would then be 9 particle diameters or 27 cm high. The SGP for various gasifiers are shown in Table 3.

1.10.5 Gas Energy Content

Fuel gases are rated as low, medium and high in energy content and the energy contents of these gases are shown in Table 4. This is obviously a very coarse separation of the gases that occur.

Table 4 – Heating value of Low, Medium and High Energy Gas

Name	(MJ/Nm3)	(Btu/scf)
Low energy gas	4-12	100-300
Medium energy gas	12-24	300-600
High energy gas	>24	>600

Table 5 - High and Low heating Value of the major Gas Components

Component	Symbol	HHV (MJ/Nm3)	LHV (MJ/Nm3)	HHV (Btu/scf)	LHV (Btu/scf)
Hydrogen	H_2	13.2	11.2	325	275
Carbon monoxide	CO	13.1	13.1	322	322
Methane	CH_4	41.2	37.1	1013	913

(1 Btu/scf = 40.672 kJ/Nm3 ; Normal conditions; 0°C, 1 Bar; standard conditions, 60 °F, 1 bar) from [Reed, 1988] p. 53

Gas produced with air typically contains 50% nitrogen as a diluent and is classified as a low energy gas. Use of oxygen or pyrolysis processes produces medium energy gas. Synthesis gas ($CO + H_2$) can be converted catalytically to high energy gas methane, CH_4, but the effort is seldom justified.

Table 6- Typical gas producer analyses (in Vol %) from updraft, downdraft and fluidized bed gasifiers

Gasifier Gas Analysis	Updraft [1]	Circulating Fluidized Bed[2]	Downdraft [3]
Hydrogen	6.9	11.2	15.2
Carbon Monoxide	29.5	20.2	22.1
Hydrocarbons	2.2	5.8	1.7
Carbon Dioxide	6.1	12.0	9.7
Nitrogen	55.3	44.6	50.8
Heating value (MJ/Nm3)	5.53 (gross, dry basis)	5.86	5.80

[1][McLellan, 1996], [2][Albrecht, 1996], [3][Reed, 1988], p. 24.

In the U.S. energy is usually rated by the **high heating value (HHV)**, the value based on liquid water as one of the products the value which is obtained in the bomb calorimeter. However, there are very few installations that recover the heat of vaporization and water is generally exhausted as steam. The **low heating value (LHV)** is based on water leaving the process as a gas. This value is used in Europe and most of the rest of the world.

A peculiar situation has arisen between metric and English unit countries. The use of HHV to calculate fuel energy in the U.S. limits the efficiency of stoves and furnaces to about 90%. In the rest of the world the LHV is used to rate appliances. Thus stoves imported to the U.S. from Europe are rated to have 10% higher efficiency than their counterparts used in the U.S. Conversely, many countries in Europe use condensing systems that recover the heat of vaporization; many of these systems can have efficiencies over 100% wben fuels are rated on a HHV basis.

Table 5 lists the high and low heating values of the principal components of producer gas. The heating value of any specific gas can be calculated from a composition list using these figures.

A typical gas from an updraft, downdraft and fluidized bed gasifier is shown in Table 6.

If a gas is to be used locally for heat generation there is little difference between these energy levels; burners for very low energy gas are available. However, it the gas is to be used for generating power in engines use of a low energy gas results in derating of the engine power unless supercharging is used. If tbe gas is to be transported over a km or more distance, low energy gases require uneconomically large pipes and fittings.

1.11 GASIFIER PROBLEMS

1.11.1 Biomass Drying and Comminution

A major "hidden issue" in biomass thermal conversion is the importance of drying biomass before use and reducing it to a size suitable for gasification. Petroleum fuels do not dissolve water, and so are sold dry (though many scalawags try to sell "water burning" schemes). Biomass can easily contain 50% water without looking any different (but it feels cooler and heavier).

I estimate that **half the failures** in biomass thermal conversion are due to insufficient attention to drying and fuel comminution and separating. Some gasification processes can tolerate high moisture content - but they are then using high technology and high-grade energy to accomplish a task better handled with simpler equipment specifically designed and often using waste energy. While not strictly a part of biomass thermal conversion, drying of biomass is a very important practical part of all thermal processes and will be discussed in Volume II.

1.11.2 Tar Production

A major concern in gasifier design is the amount of "tar" produced. Tar, also known as creosote, is a sticky, condensable vapor that can clog engine valves and turbochargers leading to decreased performance and increased maintenance. Tar cleanup complicates the gasifier system. Many gasifier designs produce so much tar that the gas cleanup equipment cost is several times the gasifier cost. Fluidized beds typically produce 5,000-40,000 ppm, while updraft biomass gasifiers can produce 100,000 ppm.

Both the Imbert and the "stratified downdraft" gasifiers produce much lower tar levels, typically 1,000 ppm. In order to operate engines for 5,000 hours without maintenance, this level of tar must be reduced to <50 ppm.

A number of schemes have been developed to further reduce tars [Reed, 1986]. The Pyrolysis-Gasification-Combustion (PGC) laboratories at the Indian Institute of Science (IISc) in Bangalore, India, have developed a low tar gasifier. Air is injected below the flaming pyrolysis zone to gasify the remaining charcoal and give tar levels below 100 ppm [Mukunda, 1993]. A number of groups are now working with this type of gasifier.

1.11.3 The Dead Char Problem

Downdraft gasifiers also produce about 5% of the input wood as a "char-ash" with wood and up to 25% with agricultural residues. Char-ash is a much depleted charcoal that contains all the ash and whatever charcoal hasn't been converted to gas. This char-ash occurs just above the grate and is either blown through by the gas or shaken through with a grate shaker. Unfortunately, there is not enough energy in the gases hot gases emerging from the pyrolysis zone to convert all the charcoal to gas.

The new gasifier design from India mentioned above converts this char ash to energy in an additional zone by air injection near the grate.

1.11.4 Agglomeration Problem of High Ash Fuels

Agricultural residues, such as rice hulls, nut hulls, straws and husks typically have a 5%-20% mineral content, mostly dispersed at the molecular level. Agricultural residues are potentially more important than woody biomass for energy, because they occur where food is produced and people live.

They are often burned off the field to make way for the succeeding crop. Recovery of the minerals can recycle them for the next crop.

Low temperature oxidation of ag residues can release the minerals as a submicron "smoke" that would require a baghouse for removal. High temperature direct combustion of these materials on the other hand produces volatile species, particularly of alkalis which can produce deposits of slag on critical surfaces. Direct combustion can also impede complete combustion by forming a slag "cocoon" around the charcoal. Finally high temperature combustion can cause enough agglomeration to produce slag and clinkers which are difficult to remove from tbe system.

Gasification of residues can minimize these problems, because the required temperatures need not exceed 900 °C, (although they do in some gasifiers).

1.12 THE WORLD STATE OF GASIFICATION

One could write a book on gasifiers simply by referring to recent publications on the subject and many sucb books are published. However, this "second band" data does not always give a realistic view of tbe various projects. Therefore, we decided to make "site visits" to as many of the gasifier projects as was practical for this book. One of us (TBR) made a "Gasification Odyssey" from September to November 1996, taking advantage of a "round the world" airline fare and E-mail for arranging the schedule and visits. There are a number of "site visits" made at that time and reported here. (Some reports rely on recent visits by tbe authors or others made in the last few years. A few "historical projects" are included of special types of gasifiers.) Our apologies to groups that couldn't be included, but we bope they are found in the database.

One inevitably gets an overall impression from such a large number of visits. I will attempt to give here an overview of the state of gasification as I saw it on this trip.

1.12.1 Large gasifier projects (>10 MWe)

The United States, Canada and the Scandinavian countries and Finland have both very large forest resources and paper and lumber industries dependent on these resources. These industries are equipped to bandle hundreds or thousands of tons of wood every day. It is natural that they have turned their interests to gasification on a very large scale. It is generally agreed that fluidized beds are most suited for large scale (> 10 MWe, or 10 tons/hr) gasification. I visited a number of such plants in Sweden, Finland, Hawaii and Vermont. The y require large scale engineering and finance and typically require many years in the planning and financing stage before they can be tested. However, there are a several such plants that can be considered to have reached the "commercial" stage and several more approaching that goal.

One of the major goals of sucb large gasifiers is to generate power in an Integrated Gasifier and Combined Cycle (IGCC) plant with efficiencies over 40%. One such plant has already operated in Varnamo, Sweden. Fluidized beds typically generate 1-2% "tar" in the gas - no problem if the gas is to be burned directly. The tar and particulate need to be removed if the gas is to be used in an IGCC plant and a great deal of work is being performed on catalytic tar cracking and ceramic filtering of the gases from fluidized bed gasifiers.

1.12.2 Small scale gasifiers (0.01-5 MWe)

As mentioned above, there was a perception in the 1980s that gasifiers for heat and small scale gasifiers had already been proven. Therefore, all the support for gasification focussed on large gasifiers. I was surprised in visiting Denmark, the Netherlands, Switzerland and India to find that almost all of the interest is focussed on smaller gasifiers - more appropriate to the dispersed nature of biomass resources.

There is a great deal of work going on in the field of smaller gasifiers all around the world, and recently the U.S. Department of Energy has shown interest in distributed power and smaller gasifiers.

1.12.3 Cooking Stove Gasifiers

It has now been found possible to make gasifiers even smaller for domestic cooking. This relies on the principle of the "inverted downdraft gasifier" in which ignition is at the top of a cylindrical vessel containing wood chips, sticks, pellets etc. and air enters at the bottom, passing up by natural or forced convection.

The natural convection stoves (inverted downdraft; top-lighted, charcoal making) stoves are the simplest to build and operate. An excellent clean hurning stove can be made from two coffee cans. They require a chimney-burner above the fuel bed in which the rising pyrolysis gas burns in the naturally inspirated air. They typically burn down in 10-60 minutes, leaving about 25% excellent charcoal [Reed, 1996].

Forced convection stoves burn more intensely with better control. They require typically a very small (2 W) blower and generate 3-5 kW thermal [Reed, 1999].

Both types of stove can be started, burned and extinguished indoors without odor. We have cooked a number of dishes in my wife's kitchen.

1.12.4 Gasifiers for Heat, Power or Synthetic Fuels?

Gasifiers can produce gas to be used for **heat applications** such as

- Drying
- Brick and Cement making
- Glass making
- Domestic Cooking
- Operation of Steam turbines for electric power
- Food Processing
- Boiler conversion

The production of gas for these uses is relatively simple, requiring a minimum amount of tar removal, provided the gas is kept hot enough to prevent tar from condensing in the delivery pipes and burner. In the 1970s it was believed that these gasifiers could he commercialized immediately, and little support was provided for their development. As a result, they have been slow to develop, hut represent the majority of operating gasifiers today.

Because of the necessity of keeping the gas hot to prevent tar formation, "close coupled" gasifiers have developed in which the gasifier and combustion unit are in the same shell. The US Government has encouraged the use of alternate energy sources with tax credits for gasification (hut not combustion) of biomass. It becomes a legal issue whether a close coupled gasifier-combustor is eligible for credits, and sometimes the gasifier section is owned by one legal entity while the combustor is owned by another.

Gas can also be used for production of power in

- Diesel engines
- Spark and Gas engines
- Gas turbines
- Stirling engines
- Fuel Cells

The second list is typically a higher value use than the first. However, the Achilles heel of biomass gasification is the sometimes high content of "tars" which can clog up delivery lines and valves on engines. As a result, most successful commercial gasifiers to date have been for production of heat. A great deal of effort is being spent now to make low tar gasifiers and/or to remove tars by filtration or catalytic or thermal cracking.

Finally, gasifier can be used for chemical synthesis through the route of synthesis gas.

1.13 A GASIFIER DATABASE ON THE WORLD WIDE WEB

We have established a web page for the Biomass Energy Foundation, at www.webpan.com/BEF and we urge you to visit that page for recent news in gasification. Chapter 2 contains a database on gasifiers used in the preparation of this book. It can also be found at our web page. It is our intention to keep it up to date. If any reader has corrections, please send them to the BEF, reedtb@CS.COM or fax to 303 278 0560. that has an updated version of the database in Chapter 2. We also have a data base of proximate and ultimate analyses on 300 forms of biomass. Our site bas links to many other energy sites related to biomass gasification. As we go to press, we have checked the information in our database hy E-mail.

1.14 THE INFORMATION TIDAL WAVE: NEWSLETTERS, E-MAIL AND THE WORLD WIDE WEB

The world of information is changing very rapidly with the advent of desktop publishing, faxing, E-mail and the World Wide Web. Peter Drucker, a management sage, says: "There is no real comparison of the Information Revolution with the Industrial Revolution. What is bappening now is far more profound!"

This book would bave been very different without the recent advances in information gathering and transmission. In September-November, 1996, I took a six week "Gasification Odyssey" around the world, stopping in 9 countries to visit gasification sites. As the various projects were described the draft was E-mailed or faxed to the contact person for editing. New gasifier projects were discovered on the World Wide Web.

We hope soon to have a searchable bibliography of over 3,000 papers on gasification prepared by Prof. P. P. Parikh at the Indian Institute of Technology in Bombay available on the WWW.

There is an enormous amount of information available in more transient form from newsletters, E-mail and the World Wide Web. Most of these groups maintain files and are very cooperative in supplying information.

Desktop publishing has contributed many valuable newsletter groups that collect information relevant to the field of gasification. The US Congress in 1987 funded five regional biomass agencies comprising the Northeast, Northwest, Great Lakes, Southern and Western regions of tbe U.S. These groups fund work in gasification and other fields. Some of these issue useful monthly newsletters which give the latest updates on gasification (and other projects) in tbeir regions and list upcoming events of interest. [SERBEP, 1997; WRBEP, 1997].

The Indian Institute of Science in Bangalore publishes the Biomass Users Network, India, BUN-INDIA newsletter with many excellent articles on gasification [BUN, 1997]. In the Asia-Pacific Region the Food and Agriculture Organization of the United Nations publishes (sporadically?) "Rural Energy", edited by Naksitte Coovattanacbai [FAO, 1994]. The Stockholm Environmental Institute publishes a bi-monthly newsletter, "Renewable Energy for Development" [SEI, 1997] which discusses gasification among other renewable energy subjects.

This flood of information has both positive and negative consequences for the world of gasification. It behooves anyone interested in this area to know how to use electronic communication - but not to forget all past skills in the exploding land of information exchange. We tend to forget that information exchange doesn't create new information - just makes current information more widely available. For this reason, we hope that this book will not be made obsolete, but will be supplemented by E-mail and the WWW.

The E-mail system is estimated to bave 100 million users around the world. I a, the moderator for the GASIFICATION group and have addresses for several hundred people interested in gasification in a dozen countries and we correspond continually. The largest cluster interested in gasification is in the Center for Renewable Energy and Sustainable Technology, **CREST** (and the National Bioenergy Industries Association). They can be found on the Worldwide Web at www.crest.org.

CREST has lists of people interested in BIOENERGY (300), GASIFICATION (150), STOVES (100), BIOMASS CONVERSION and many other topics in renewable energy who regularly correspond with each other. The STOVE group is actively investigating many kinds of cookstoves including the new wood-gas stoves (see Section 1.13.3).

Current subscribers to the list are engaged in the research and commercial production of biomass crops and fuels, the conversion of biomass power in commercial operating plants, the construction and testing of commercial scale pilot facilities for combustion, gasification and anaerobic digestion, testing and analysis of environmental impacts for bioenergy, and promotion and planning of future bioenergy resources. This is a cooperative, volunteer effort that is now in it's fifth year. The lists are moderated and managed by volunteers. Any of these groups can be joined by sending the message:

"subscribe *gasification*" (Use a separate line to subscribe to *bioenergy*, *stoves etc.*)"

to the E-mail address "majordomo@crest.org". Mr. Tom Miles Jr. is the very helpful moderator for bioenergy, I (TBR) am the moderator for gasification along with Prof. Esteban Chornet. If you wish to leave the list, simply send the message "unsubscribe gasification". The majordomo address is completely automatic and will add you to the list and send you instructions on how to access past digests of letters, find who is on the list etc. To post a message to all members on the list, address it to listname@CREST.ORG (Example: gasification@crest.org)and it will automatically go to everyone.

Introduce yourself and your interests. Soon you will know others and write them privately on particular subjects. Please keep track of individual addresses and DON'T send messages to *gasification* when they are only intended for one person.

The World Wide Web is fast becoming the first place to look for information on any subject, with thousands of new "pages" being added each week. An important feature of the WWW is the use of "search engines" to find your data in the ethernet.

1.15 THE BIOMASS ENERGY FOUNDATION

During World War II Dr. Harry LaFontaine manufactured gasifiers in Denmark as a cover for his activities in the Danish Underground (including a gasifier powered torpedo boat). When the so called "Energy crisis" made us conscious about our fossil fuel vulnerability in 1974 Harry recalled this experience and helped write several books about gasification and lectured at dozens of universities in the East.

In 1983 Harry LaFontaine formed the Biomass Energy Foundation, BEF, as a 501-C-3 tax exempt organization to sponsor his energy activities. In 1987 I became a Vice President of the BEF and started the BEF Press to keep books on gasification in print.

I now re-publish a dozen "classic" books on biomass gasification through the Biomass Energy Foundation Press (a 501-C-3 not for profit entity) [BEF PRESS, 1998]. In the last year there have been more orders for books on gasification than in the five previous years.

Harry LaFontaine died in 1995 and left the Biomass Energy Foundation to me. I have also used it to support my activities in gasification, including much of the writing of this book.

I have been given multi-file box collections of papers on gasification used in writing several books. I have recently **discarded** thousands of papers and reports from before 1980 - while keeping dozens that still looked interesting. The gleanings from this literature will appear in Volume II, "Science and Engineering of Gasification".

1.16 WORD USAGE

Any newcomer in this field will be confused by the wide assortment of new words. A clear understanding is based on the clear definition and use of words. Yet, each person uses words as they please and often with different meanings from those used by his listener. We have tried to be careful to define the terms used in this book. You are free to disagree with these definitions, but having read them you will know our intended use.

Any newcomer in this field will be confused by the wide assortment of names used for gasifiers. Each new inventor of a gasifier wants to find a new name to distinguish it from previous gasifiers. The difference may be major – or trivial. The reader needs to approach the various names with enough knowledge of the principles of gasification and the various ways of applying these principles to the wide variety of situations where gasification is useful.

1.17 ENERGY UNITS FOR BIOMASS & ENERGY-SPEAK

There are two dominant scientific systems of units in the energy world - the SI, "Systeme Interationale" (m, g, sec), universal in most of the world, and the older English system with its BTUs, pounds and feet. Much of the early science and engineering of energy was done by the English and

Americans, so some of us have historic and sentimental ties to that system. However, a new century is dawning and it will progress faster and be more harmonious if we all speak the same language. (The world is also progressing toward a common second language - English - for commerce and politics, so losing English units will be more than compensated by gaining the English language - a fair trade.)

Anyone working in the energy field needs to be fluent in both languages. For 25 years in the U.S. I have espoused metric units - but I spoke and wrote more in English units than Metric. I have found during the writing of this book that I was beginning to "speak and think metric" more and more (and faster and faster). It is high time in my estimation that U.S. thinking joins the rest of the world in the energy (and other) fields. Therefore, this book will be written in "metricese". A Unit Conversion Table is included as Appendix B to permit translation from the older units. We may occasionally also offer the English equivalents.

Calories are slowly being replaced by Joules (1 cal ~ 4 J (4.187 J). The terms kWth and kWe bridge the gap between SI and English units, since Watts are identical in both systems.

It is fashionable to think that we don't need to remember facts - we only need to know where to find them. This is a prescription for disaster. Original thinking requires a working knowledge of approximate reality. In that spirit I offer the following commentary.

While every biomass fuel is different, there are a number of handy approximations suitable for approximate discussions of "biomass" and used by those long in the field, a form of "energy-speak". Those of us working in the laboratory will tend to use the smaller units, those involved with process design will use the larger units. Thus, The energy content of "realistically dry" biomass (10% MC) is ~18 MJ/kg, ~18GJ/tonne, (8,000 Btu/lb or 16 MBtu/ton).

1 kW-hr is 3.6 MJ or 3,430 Btu/hr. This leads to the useful approximations that consumption of either 1 tonne/h or 1 ton/h of biomass generates approximately 5 MWth, 1 MWe (at 20% efficiency) or 2 Mwe (40% efficiency).

A cubic meter, m^3, of producer gas weighs approximately 1 kg. Therefore, 100 ppm or tar or particulate weighs 100 mg.

1.18 REFERENCES AND RECENT LITERATURE

References used in this volume, along with other useful gasification references are found in Chapter 8 and at the end of each chapter.

Biomass has been somewhat of an "orphan" in the solar energy literature. It supplies about 4% of U.S. energy, and up to 60% in some countries of the world. Yet, when "solar energy" came to prominence after the first oil crisis in 1974, it focused largely on new, high tech energy sources such as solar-thermal, photovoltaic, wind generators and geothermal, ignoring the largest solar-renewable source of all, biomass. The "biomass energy" proponents were not represented in the early solar energy journals and meetings.

Because biomass often enjoyed government support, much of the work was presented in government meetings here and abroad. There was a great deal of gasification work done in the 1980s and much of this appears in reports of the U.S. Department of Energy and the International Energy Agency (IEA). The DOE work is very well summarized in [Stevens, 1994]. Work of the International Energy Agency appears many places such as [Ferrero, 1992]. Most energy conferences over the years have had sections devoted to gasification. In particular we have relied heavily of the "Assessment of

Thermochemical Conversion Systems" [Bridgwater,1993] and the minutes of the "Large Scale Gasification Systems" workshop [Kaltschmitt, 1996] for large scale industrial gasifiers. For the current state of small gasifiers we have used the "UNDP/WB Small-Scale Biomass Gasifier Monitoring Report".[Stassen, 1993].

CHAPTER 2 – A GASIFIER DATA BASE

2.1 INTRODUCTION

It is hard to find one's way around the world of gasification without a program. This chapter contains a database to help the reader find specific gasifiers. Some of the gasifiers are described at greater length in the following chapters of the book. Chapter 3 examines large gasifier systems, Chapter 4 describes details of selected small gasifiers and Chapter 5 contains information on gasification research institutions. Inevitably the placement is somewhat arbitrary.

We are fortunate indeed to have the ability to obtain instant information through the Worldwide Web and to be able to discuss it on E-mail. There are many sites on the Web for specific gasifiers, there are more general sites for gasifier research and support organizations, and there are usually links to other even more general biomass energy sites. However, books such as this provide an important guide to a deeper understanding of the instant information which can't be obtained by "surfing the web".

I recommend that anyone interested in gasification join the GASIFICATION division of the Center for Renewable Energy and Sustainable Technology, CREST where I am webmaster. Just send the message "subscribe gasification" to majordomo@crest.org. If you don't want to stay, send the message "unsubscribe gasification" to the same address.

I used the Microsoft ACCESS software to enter the data. I continue to store the data there. The database also fits very well on a spreadsheet, and I have used an EXCEL spreadsheet that can be viewed of downloaded at www.woodgas.com (and imported to other spreadsheet programs such as Lotus 123).

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This is the second edition of "Survey of Biomass Gasification – 2001". I have updated the earlier database, based on communications from the entry members. I will probably make corrections and additions again in 2002, so if you find errors or wish to have an entry, send me an Email at reedtb2@cs.com. If you are new in the field, fill out the form below and mail it to me. Since a database is a continually changing document, the database printed here will slowly change as new entities enter the field and old ones occasionally leave. I will also update the database at our new website at www.woodgas.com.

2.2 THE BIOMASS GASIFICATION DATABASE

The actual gasifier database has sixteen fields and 160 records and is still growing. The fields are

- DATE of most recent entry.

- ORGANIZATION (Name of company, system or organization)
- CATEGORY (Large gasifier Systems (Chapter 3) Small scale gasifiers (Chapter 4), Research and Support, Manufacturers and consultants)
- PURPOSE AND DESCRIPTION
- COUNTRY
- CONTACT (name of principal contact)
- PHONE/FAX (Phone number and fax in that order
- E-MAIL
- WWW PAGE (Web page if available)
- ADDRESS (full address)
- STATUS (Current status of organization)
- FUELS (fuels actively tested or planned)
- SIZES (Sizes made or planned)
- YEARS (years in business)
- UNITS BUILT (number of units actually built or under construction)
- COST (Particular cost or preferably cost/kWth or cost/kWe of system)
- COMMENTS
- DATE ENTERED

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The database is much too big to print in this book. We are including here a shorter subset of the above list for ready reference including

- ORGANIZATION (Name of company, system or organization)
- CATEGORY (Large gasifier Systems (Chapter 3) Small scale gasifiers (Chapter 4), Research and Support, Manufacturers and consultants)
- PURPOSE AND DESCRIPTION
- COUNTRY
- CONTACT (name of principal contact)
- PHONE/FAX (Phone number and fax in that order
- E-MAIL

I hope you find the information useful.
~~~~~~

ORGANIZATION	CATEGORY	PURPOSE/DESCRIPTION	COUNTRY	CONTACT	PHONE/FAX	E-MAIL
ADVANCED ALTERNATIVE ENERGY CORPORATION	GASIFIERS - SMALL	Gasification systems for demand or supply of heat and power	USA	Les Blevins	785 842 1943 785 842 0909	lbj@cjnetworks.com
AERIMPIANTI (Ansaldo, TPS)	GASIFIER SYSTEMS-LARGE	Fuel gas for cement kiln of power, 2 Circulating TPS FBs	ITALY	G. Campagnola	39 2 54 97241 39 2 54 97300	
AEW (Associated Engineering Works)	GASIFIERS-SMALL	Low tar downdraft thermal and power gasifiers	INDIA	G. M. Satyanarayana	91 8819 22950 91 8819 24572	
ALABAMA, UNIVERSITY OF	RESEARCH & SUPPORT	Pyrolysis and gasification	USA	Michael Eley	205 895 6361	
AMBIENT ENERGY LTD.	GASIFIER SYSTEMS LARGE	Build large biomass power plants in UK	UK	Gerry Swarbrick	44 117 914 7158 44 117 949 3063	gjswarbr@netcomuk.co.uk
AMERICAN HIGH TEMP INC.	GASIFIERS-SMALL	Clean up-down draft gasifier for power	USA	Kevin McDevitt	603 625 6669 603 627 8670	kip2251@aol.com
ANKUR SCIENTIFIC ENERGY TECHNOLOGIES	GASIFIERS-SMALL	Low tar downdraft gasifiers for Steam, Power, thermal energy, irrigation	INDIA	B. C. Jain	91 48 1021 91 48 1042	ankur.energy@smn.sprintrpg.ems.vsnl.net.in
APROVECHO	GASIFIERS-SMALL	Small gasifiers	USA	Larry Winiarski	541 753 4921	larryw@proaxis.com
ARBRE (TPS)	GASIFIER SYSTEMS-LARGE	8MW CFB demonstration of IGCC & Short rotation forestry	UK	Keith Pitcher	? 44 113 224 42384	
ASIAN INSTITUTE OF TECHNOLOGY (AIT)	RESEARCH & SUPPORT	Research in alternate energy, gasification	THAILAND	Prof. Bhatacharya	66 2 524 5403 66 2 524 5439	bhatta@ait.ac.th
ASSIDOMN KRAFTLINER	GASIFIER SYSTEMS-LARGE	94186 Pitea	SWEDEN	Gunnar Lundkvist		Gunnar.lundkvist@asdo.se
ASTON UNIVERSITY	RESEARCH & SUPPORT	Research and evaluation of gasification, pyrolysis	UK	Tony Bridgwater	44 21 359 3611 44 21 359 4094	a.v.bridgwater@aston.ac.uk
B9 Energy Biomass Ltd.	GASIFIERS-SMALL	Demonstration of Gasification at Museum	IRELAND	Debra Jenkins	44 0504 271520 44 0504 308090	
BATTELLE COLUMBUS LABORATORIES, BCL	RESEARCH & SUPPORT	Research gasifier for 2 FB pyrolytic gasifier	USA	Mark A Paisley	614 424 4958 614 424 3321	Paisley@battelle.org
BERA (The Biomass Energy Research Association)	RESEARCH & SUPPORT	Lobby for biomass utilization in U.S. Congress	USA	Donald L. Klass	202 785 2856	

ORGANIZATION	CATEGORY	PURPOSE/DESCRIPTION	COUNTRY	CONTACT	PHONE/FAX	E-MAIL
BG TECHNOLOGIES USA, INC	EQUIPMENT & CONSULTING	Turnkey gasification energy systems	USA	Wm. E. Partenen	410 740 3025 208 728 8983	bpartenen@bgtllc.com
BIG-GT (State Bahia, Brazil, Electro-Braz, Shell, World Bank)	GASIFIER SYSTEMS-LARGE	Biomass Integrated Gasification with combined cycle to prove commercial viability of atmospheric BIG-CC	BRAZIL	Eduardo Carpentieri	55 81 228 2605 55 81 227 2785	carpent@elogica.com.br
BIOELETTRICA (Energy Farm projectof E.C. in Italy)	GASIFIER SYSTEMS-LARGE	Demonstration of short rotation forestry, using Lurgi CFB gasifierIGCC	ITALY	Henk de Lange	39 050 535 479 39 050 535 477	delange@bioelectrica.it
BIOMASS ACTION RESEARCH CENTRE	RESEARCH & SUPPORT	Consulting pyrolysis and gasification	INDIA	P. D. Grover	91 65 65 4189 91 65 66 7088	pdgrover@netearth.ernet.in
BIOMASS ENERGY FOUNDATION (BEF)	RESEARCH & SUPPORT	Gasification research, studies and publication of books	USA	Thomas B. Reed	303 278 0558 303 278 0558	reedtb@compuserve.com
BIOMASS GASIFICATION FACILITY (BGF) (Westinghouse, PICHTR/IGT, US DOE)	GASIFIER SYSTEMS-LARGE	Pressurized Bubbling FB, Renugas Process, for IGCC	USA	Ben Wiant	808 579 8020 808 579 9812	bgfmaui@maui.net
BIOSOLUTIONS USA, INC.	GASIFIERS-SMALL	Tower type chnnelized bed gasifier systems for heat and power	USA	Robert M. Stwalley III, PhD, Pres.	765 409 7463 765 420 7830	bstwalley@yahoo.com
BIOSYN	GASIFIER SYSTEMS-LARGE	Oxygen gasifier for methanol production	CANADA	Prof. Esteban Chornet	819 821 7171 819 821 7955	echornet@coupal.gcm.usherb.ca; esteban_chornet@nrel.gov
BIOSYSTEMS ENERGY, LTD	GASIFIERS-SMALL	Novel design	NEW ZEALAND	Ian Kearney	64 03 544 5556 64 03 544 0374	
BRIGHTSTAR SYNFUELS CO.	GASIFIER SYSTEMS-LARGE	Externally heated, steam reforming of biomass, for medium Btu syngas	USA	Ron Menville	504 642 2500 504 642 2503	ronmenvillejr@worldnet.att.net
BTG (Biomass Technology Group)	RESEARCH & SUPPORT	Fluidized and Fixed bed DD, CHP, and other gasification research, Consulting	NETHERLANDS	H. Knoef	31 53 489 2897 31 53 489 3116	knoef.btg@ct.utwente.nl
BUCK ROGERS	GASIFIERS-SMALL	Downdraft gasifier, retrofit for heat	USA	Bill Ayres	913 599 6911 913 599 2121	

ORGANIZATION	CATEGORY	PURPOSE/DESCRIPTION	COUNTRY	CONTACT	PHONE/FAX	E-MAIL
BURLINGTON ELECTRIC, VERMONT (FERCO, Battelle)	GASIFIER SYSTEMS-LARGE	IGCC Demonstration of Battelle gasifier at existing wood plant	USA	Mark Paisley	770 662 7800 770 662 7807	markpaisley@future-energy.com
CALIFORNIA ENERGY COMMISSION	RESEARCH & SUPPORT	Energy support and development of gasifiers	USA	Valentino M. Tiangco	916 654 4684 916 653 6010	valen@ns.net
CALIFORNIA PELLET MILL CO.	EQUIPMENT & CONSULTING	Manufacturer of pellet mills for biomass densification	USA	Bob Massengill	612 332 1400 612 755 3713	
CAPSTONE MICROTURBINES	EQUIPMENT & CONSULTING	Build and market small turbines (30 kW)	USA	Ake Almgren	818 716 2929 818 716 9910	
CARBON ENERGY INC.	GASIFIERS-SMALL	Design of small scale gasifiers for MSW to heat	USA	Jerod Smeenk	515 292 0887	smeenk@ames.net
CARBONA (Formerly Tampella, Enviropower, and Vattenfall)	GASIFIER SYSTEMS-LARGE	Pressurized Fluidized Bed	USA	Kari Rasanen	358 93 358 0300 358 93 358 0325	
CASCADE RESEARCH, INC.	RESEARCH & SUPPORT	Consulting, evaluation of technologies, IEA representative US	USA	Don J. Stevens	509 375 3124 509 375 3267	c.refrch@televar.com
CEMIG (Companhia Energetica de Minas Gerais)	RESEARCH & SUPPORT	Power generation from charcoal-blast furnace gas	BRAZIL	E. C. Vasconcelos		
CESP (Companhia Ebergetica de San Paulo)	GASIFIER SYSTEMS-LARGE		BRAZIL			
CHINESE ACADEMY OF AGR. AND MECHANICAL SYSTEMS (CAAMS)	RESEARCH & SUPPORT	Chinese Central Gasification Research	CHINA	Gao Xiansheng	86 10 2017131 86 10 2017326	
CHIPTEC WOOD ENERGY SYSTEMS	GASIFIERS-SMALL	Crossdraft boiler systems, new or retrofit	USA	Robert Bender	802 660 0956 802 660 8904	chiptec@together.net
CLEW (Camp Lejeune Energy from Wood)	GASIFIERS-SMALL	1 MW Downdraft gasifier power system	USA	Carol Purvis (John Clelland)	919 541 7519 919 541 7885	purvis.carol@epa.gov
COMBUSTION CONSULTANTS LTD	GASIFIER SYSTEMS-LARGE	Fixed bed close coupled gasifiers to supply clean combustion gas at over 2,000 F	NEW ZEALAND	Paul D. Williams	64-6 875 0734 64-6 875 0098	enquiries@waterwide.co.nz

ORGANIZATION	CATEGORY	PURPOSE/DESCRIPTION	COUNTRY	CONTACT	PHONE/FAX	E-MAIL
COMMUNITY POWER CORPORATION	SMALL GASIFIERS	25 kW Small Modular Biomass Power micro-utilities	USA	Robb Walt	303 690 7869 303 617 1280	robbcpc@aol.com
COMPACT POWER	GASIFIERS - SMALL	Pyrolytic gasifier for MSW, Sludge...	UK	Nick Cooper	44 242 224 243 44 242 221 273	compower33@aol.com
CONEG (Coalition of Northeastern Governors)	RESEARCH & SUPPORT	Support of Energy projects	USA	Rick Handley	202 624 8450 202 624 8463	
CONEG (Northeast Regional Biomass Program)	RESEARCH & SUPPORT	Regional biomass energy program of the US DOE	USA	Richard Handley	528 899 9572 528 899 9574	rhandley@capital.net
CRATECH	GASIFIERS - SMALL	Pressurized fluidized bed 1.2MWe gasifier for cotton trash etc.	USA	Joe Craig	806 327 5220 806 327 5570	cratech@onramp.net
CRATECH	GASIFIERS-SMALL	Developing pressurized fluidized bed gas turbine system for Ag residues	USA	Joe D. Craig, Pres.	806 327 5220 606 998 5570	cratech@onramp.net
DAIMLER BENZ AEROSPACE AG	RESEARCH & SUPPORT	Gasifier research	GERMANY	S. Girges	49 5055 598 258 49 5055 598 202	suaaraf.girges@ri.dasa.de
DANISH TECHNICAL UNIVERSITY (DTU) (Department of Energy Engineering)	RESEARCH & SUPPORT	Gasification process development, experimental systems, modelling, emissions, gas cleanup	DENMARK	Henriksen, Ulrik	45 4525 4174 45 4593 5761	uh@et.dtu.dk
DASAG (Dasad Energy Engineering Ltd.)	GASIFIERS-SMALL	Stratified downdraft for woody, and ag residues for decentralized power	SWITZER-LAND	H.Sharan	41 52 335 3500 41 52 335 1442	100343.210@compuserve.com
DECENTRALIZED ENERGY SYSTEMS, INDIA (DESI)	GASIFIERS-SMALL	Development of Fixed bed downdraft (low tar) gasifiers for village power use	INDIA	P. K. Bhatnagar	91 11 696 7938 91 11 686 6031	desi@sdalt.ernet.in
DELFT UNIVERSITY OF TECHNOLOGY	RESEARCH & SUPPORT	1.5 MWt process development unit with pressurized fluidized bed gasifier, hi T ceramic filter and gas turbine combustor	NETHERLANDS	Jans Andries	31 15 278 5410 31 15 278 2460	j.andries@wbmt.tudelft.nl

ORGANIZATION	CATEGORY	PURPOSE/DESCRIPTION	COUNTRY	CONTACT	PHONE/FAX	E-MAIL
DEMONTFORT UNIVERSITY	RESEARCH & SUPPORT	Hybrid Biomass-Wind for rural electric power	UK	Andrew P. Chick	44 1400 275624 44 1400 273708	apchick@dmu.ac.uk
DK-TEKNIK	GASIFIERS-SMALL	150 kW gasifier development	DENMARK	Henrik Jakobsen	45 39 555 999 45 39 696 002	dk-teknik@dk-teknik.dk
DK-TEKNIK	RESEARCH & SUPPORT	Danish Energy Agency; all aspects of gasification R & D	DENMARK	Soren Houmoller	45 39 69 65 11 45 39 69 60 02	houmoller@DK-Teknik.dk
DTI (Danish Technological Institute, DTI Environment, Waste Management)	EQUIPMENT & CONSULTING	Updraft pilot plant for hazardous waste. Consulting on updraft and waste.	DENMARK	Bjorn Malmgren-Hansen	45 8943 8943 45 8943 8673	bjorn.malmgren-Hansen@dti.dk
ECN-NETHERLANDS ENERGY RESEARCH FOUNDATION	RESEARCH & SUPPORT	Circulating Fluid Bed, 700 kWth; Downdraft 300 kWth	NETHER-LANDS	Johan Beesteheerde	31 224 56 4594 31 224 56 3489	biomass@ecn.nl
EK ENERGI POWER CO. LTD	GASIFIER SYSTEMS-LARGE	Fluidized Bed for Biocycle project; coal-straw cogasification	DENMARK	Michael Madsen	45 44 66 00 22 45 44 65 61 04	
ELECTRIC POWER RESEARCH INSTITUTE (EPRI)	RESEARCH & SUPPORT	Research and Technology based solutions for the Electric Industry, testing and development	USA	Evan Hughes Mgr. Biomass Power	650 855 2179 650 855 8501	ehughes@epri.com
ENERGIE-TECHNIK FROMM	GASIFIERS-SMALL		GERMANY	Jurgen Fromm	49 201 30 53 00	
ENERGY & ENVIRONMENTAL RESEARCH CENTER, U. of N. Dakota	RESEARCH & SUPPORT	Oversite of Gasifier activities	USZ	Darren D. Schmidt	701 777 5120 701 777 5181	dschmidt@eerc.und.nodak.edu
ENERTECH ENVIRONMENTAL, INC.	GASIFIERS-SMALL		USA	Kevin Bolin	404 892 9440	
ENVIROPOWER (Tampella, IGT)	GASIFIER SYSTEMS-LARGE	Recirculating Fluidized Bed Gasification	FINLAND	Kari Salo	46 8 739 60 00 46 8 739 68 02	
EPA RESEARCH TRIANGLE	RESEARCH & SUPPORT	Demonstration of 1 MW downdraft gasifier for steam and poer, see MECHEM	USA	Carol Purvis		
EPI (Energy Products of Idaho, formerly JWP)	GASIFIER SYSTEMS-LARGE	Steam, power Fluidized Bed	USA	Michael L. Murphy	208 765 1611 208 765 0503	EPI@EnergyProducts.com

ORGANIZATION	CATEGORY	PURPOSE/DESCRIPTION	COUNTRY	CONTACT	PHONE/FAX	E-MAIL
ESMAP (Energy Sector Management Assist. Program)	RESEARCH & SUPPORT	Funding and guidance for gasification programs at UNDP/World Bank, world oversite	USA	Executive Secretary		
ETSU (UK Gasification Oversite)	RESEARCH & SUPPORT		UK	Nick Barker (Project Officer)	44 0235 433 511 44 0235 432 923	
EUROPEAN COMMISION: DIRECTORATE-GENERAL FOR ENERGY (DG XVII),THERMIE	RESEARCH & SUPPORT	Support of EC Gasification gasification projects: See BIOCYCLE; ENERGY FARM; ARBRE	BELGIUM	G. L. Ferrero	32 2 295 0150	
EUROPEAN COMMISSION BIOMASS GASIFICATION TARGETED PROJECTS	RESEARCH & SUPPORT	Promote Biomass Gasification under EQUIPMENT & CONSULTING 1995 agreement	BELGIUM	G. L. Ferrero	? 32 2 295 01 50	
EVN (Energie Versorgung Nord)	GASIFIERS-SMALL	Decentralized Power and heat Production with twin-fire gasifier	GERMANY	U. Rehling	49 46 316 2147 49 46 316 2148	evn.de5 t-online.de
FEE (Society for the Promotion of Renewable Energies)	RESEARCH & SUPPORT	NGO organizing R&D for biomass gasification, lobbying, PR and support	GERMANY	Eberhard Oettel	49 30 65 76 27 06 49 30 65 76 27 08	FEE-eV@t-online.de
FERCO (Future Energy Resources Corp.)	GASIFIER SYSTEMS-LARGE	Developers of large gasifier systems for efficient power (Burlington, Binaga)	USA	Sim Weeks	404 831 9355 404 814 0549	
FERN ENGINEERING, INC.	EQUIPMENT & CONSULTING	Adaptation of gas turbines to run on producer gas, design gasif. Eqpt.	USA	Jeff Phillips	508 563 7181 507 564 4851	ferneng@capecon.net
FLEXENERGY (Formerly Reflective Energies)	EQUIPMENT & CONSULTING	Small turbine development for biomass	USA	Edan Prabhu	949 380 4899 949 380 8407	edanprabhu@msn.com
FLUIDYNE	GASIFIERS-SMALL	Downdraft gasifiers and engines for power	NEW ZEALAND	Doug Williams	64 9 838 6132 64 9 838 6132	graeme@powerlink.co.nz,p-h-energy@clear.net.nz

ORGANIZATION	CATEGORY	PURPOSE/DESCRIPTION	COUNTRY	CONTACT	PHONE/FAX	E-MAIL
FOSTER WHEELER (Formerly Ahlstrom, AB)	GASIFIER SYSTEMS-LARGE	Circulating Atmospheric & Presssurized FBs for power	FINLAND	Ragnar Lundqvist	358 5229 3314 358 5229 3309	
GASIFICATION TECHNOLOGIES COUNCIL	RESEARCH & SUPPORT		USA	James Childress, President		
GLOBAL ENERGY (AFT-IGCC)	GASIFIER SYSTEMS-LARGE	Combining Coal, MSW IGCC for clean power	USA		513 621 0077 513 621 5947	
GREAT LAKES REGIONAL BIOMASS ENERGY PROGRAM	RESEARCH & SUPPORT	Regional biomass energy program of the US DOE	USA	Fred Kuzel	312 407 0177 312 407 0038	fkuzel@cedar.cic.net
HAMBURG, UNIVERSITY OF	RESEARCH & SUPPORT		GERMANY	W Kaminsky, Norbert Grittner	49 40 4123 3173 49 40 4123 6008	
HAWAII NATURAL ENERGY INSTITUTE (HNEI)	RESEARCH & SUPPORT	Research renewable energy	USA	Scott Q. Turn	808 956 2346 808 956 2335	ssturn@hawaii.edu
HAWAII, UNIVERSITY OF	RESEARCH & SUPPORT	Gasification R&D	USA	Jiachun Zhou		jiachun@hawaii.edu
HERMAN RESEARCH PTY LTD	GASIFIER SYSTEMS-LARGE	IDGCC gasification system for power generation from high moisutre fuels	AUSTRALIA	Terry Johnson	61 3 9565 9888 61 3 9565 9777	hrl@hrl.com.au
HEURISTIC ENGINEERING INC.	GASIFIERS-SMALL	Wet wood, 2 stage gasifier or Combustor	CANADA	Malcolm D. Lefcort	604 263 8005 604 263 0786	mlefcort@compuserve.com
HTV ENERGY	GASIFIERS-SMALL	Downdraft gasifier, engine, turnkey operation	SWITZER-LAND	P. Juch	41 62 216 5844 41 62 216 5109	
HURST BOILER & WELDING CO.	GASIFIER SYSTEMS-LARGE	Underfed stoker gasifier-combustor for Heat, power, steam	USA	Gene Zebley	912 346 3545 912 346 3874	hboiler@rose.net
HYDRO-QUEBEC	RESEARCH & SUPPORT	Support of renewable energy	CANADA	Beorges Aabiad		admcom@mail.dcrp.hydro.qc.ca
HYDROMAX	GASIFIERS-SMALL		USA	Marc Kalish	212 385 7560	
HYDROTEST	GASIFIERS - SMALL	Down-Updraft gasifier systems	SWITZERLAND	Willy Gemperle	41 420 44 77 41 420 44 76	

ORGANIZATION	CATEGORY	PURPOSE/DESCRIPTION	COUNTRY	CONTACT	PHONE/FAX	E-MAIL
IDAHO ENERGY DIVISION	GASIFIERS-SMALL	Demonstrate gasification for home energy needs with residential pellet gasifier	USA	Gerald Fleischman	208 327 7959 208 327 7866	gfleisch@idwr.state.id.us
IEA BIOENERGY	RESEARCH & SUPPORT	Operating agent for task 13 (biomass utilization)	USA, EEC			c.refrch@televar.com
IMTRAN VOIMA	GASIFIER SYSTEMS-LARGE	Combined cycle powerprocess using steam drying, injection	FINLAND	S. Hulkkonen	358 9 8561 4612 358 9 563 2225	weppo.hulkkonen@ivo.fi
INDIAN INSTITUTE OF SCIENCE - BANGALORE	RESEARCH & SUPPORT	All aspects of Gasifier Research, development and dissemination for India	INDIA	Mukunda, H. S.	91 80 348 536 91 80 341 683	mukunda@cgpl.iisc.ernet.in
INDIAN INSTITUTE OF TECHNOLOGY, BOMBAY (Gasification Action Res. Center)	RESEARCH & SUPPORT	Engine-gasifier research, 15 kW dual fuel diesel gasifier, damper.	INDIA	P. P. Parikh	91 572 3496 91 572 2545X7548	parikh@me.iitb.ernet.in
INRA (AFRICA Gasification)	RESEARCH & SUPPORT	Development of small scale gasifiers in Africa	FRANCE	Riedacker	? 33-1-4670 4113	riedacke@worldnet.fr
INSTITUTE OF GAS TECHNOLOGY (IGT)	RESEARCH & SUPPORT	Presssurized Fluid Bed tests on Renugas system; Processes for Power, Methanol	USA	Suresh P. Babu	847 768 0509 847 768 0516	babu@igt.org
IOWA STATE UNIVERSITY	RESEARCH & SUPPORT	5 t/d FB gasifier for agricultural wastes, corn, and switchgrass	USA	Robert C. Brown	515 294 8733 515 294 3261	rcbrown@iastate.edu
IVD (Institute for Process eningeering, Univ. of Stuttgart)	RESEARCH & SUPPORT	R&D in gasification of all biomass and fossis fuels for power generation	GERMANY	Christian Storm	49 711 685 3745 49 711 685 34	storm@ivd.uni-stuttgart.de
KAMENGO TECHNOLOGY, INC.	EQUIPMENT & CONSULTING	Non-consolidating feeder system	CANADA	Nazmir Bundalli	604 270 9995 604 270 9921	
KANSAS STATE UNIVERSITY	RESEARCH & SUPPORT	Stratified downdraft gasifier research, theses	USA	Walter P. Walawender		

ORGANIZATION	CATEGORY	PURPOSE/DESCRIPTION	COUNTRY	CONTACT	PHONE/FAX	E-MAIL
KEMESTRIE, INC.	RESEARCH & SUPPORT	Development of commercial fluidized bed and other processes from Sherbrooke U. research	CANADA	Nicolas Abatzoglou, Dir. En. & Env.	819 569 4888 819 569 8411	kem@interlinx.qc.ca
KTH (Kungl Tekniska Hogskolan)	RESEARCH & SUPPORT	Research on all aspects of gasification	SWEDEN	Krister Sjostrom	46 8 790 82 48 46 8 10 85 79	Krister@chemtech.kth.se
KVAERNER ENVIROPOWER INC.	GASIFIER SYSTEMS-LARGE		USA	Herbert. J. Fruth	410 356 1111	
LESLEY MFG. CO.	GASIFIERS-SMALL		USA	913 842 1943		
LESLIE MFG. CO.	GASIFIERS-SMALL		USA	Les Blevins	913 842 1943 913 842 0341	
LOTERIOS (Waste reclaim Loterios)	GASIFIERS-SMALL	MSW pyrolysis gas for MSW processing, disposal	USA	Gail A. Brichford	713 977 5854 713 977 6428	
LUND INSTITUTE OF TECHNOLOGY (Dept. of Chemical Engineering)	RESEARCH & SUPPORT	Operaton and ecomics of pressurized circulating and bubbling fluid bed gasifiers	SWEDEN	Prof. Ingemar Bjerle	46 8 681 91 00 46 8 19 68 26	
LURGI UMWELTTECHNIK GMBH	GASIFIER SYSTEMS-LARGE	Circulating Fluid Bed Gasifier for power generation, cement or lime kilns	GERMANY	Rainer Reimert	49 69 5808 3530 49 69 5808 2628	
Marick Gasification Ltd.	GASIFIERS-SMALL	Downdraft gasifier/gas engine for power, heat	UK	Donald C. Patrick	44 1925 220338 44 1925 220135	donaldp@marick.co.uk
MARTEZO	GASIFIERS-SMALL	Downdraft Gasifier for SI Engines	FRANCE	Marielle Touillet	33 5 49 37 02 03 33 5 49 37 39 79	Martezo@cyberscope.fr
MINISTRY OF AGRICULTURE OF THE PRC (MOA)	RESEARCH & SUPPORT	Evaluation of China's biomass capability and research on village gasifiers	PRC	Ralph Overend	303 275 4450 303 275 2905	ralph_overend@nrel.gov
MNES (MINISTRY OF NON-CONVENTIONAL ENERGY SOURCES)	RESEARCH & SUPPORT	Support of biomass gasification in India	INDIA	N. P. Singh	91 11 436 1920 91 11 436 1298	secmnes@x400.nicgw.nic.in
MORBARK INDUSTRIES	GASIFIERS-SMALL	Cyclonic Gasifier	USA	Jerry Demslow	517 866 2381	

ORGANIZATION	CATEGORY	PURPOSE/DESCRIPTION	COUNTRY	CONTACT	PHONE/FAX	E-MAIL
NATIONAL RENEWABLE ENERGY LABORATORY (NREL)	RESEARCH & SUPPORT	Downdraft air/oxygen gasification, lab facilities available	USA	Dave Dayton	303 384 6245 303 384 6103	david_dayton@nrel.gov
NEBRASKA, UNIVERSITY OF	RESEARCH & SUPPORT	Spouted Bed gasifier	USA	Dave Clements,	402 472 0177	
NEW ENGLAND POWER SERVICE	GASIFIER SYSTEMS-LARGE		USA	Raymond L. Coxe	508 366 9011 X 3120	
NEWCASTLE, UNIVERSITY OF (Chemical and Processs Engineering Dept.)	GASIFIERS - SMALL	Fixed Bed Downdraf CHP	UK	Dogru, Murat	44 191 222 60009 44 191 222 5292	Murat.Dogru@newcastle.ac.uk
NEWCASTLE, UNIVERSITY OF, AND WASTE TO ENERGY LTD.	GASIFIERS-SMALL	Small manufacturer, Research & support; Equipment & consulting	UK	Murat Dogru	00 47 1787 44 1787 373007 44 1787 373535	murat.dogru@newcastle.ac.uk
NIMBKAR AGRICULTURAL RESEARCH INSTITUTE (NARI)	RESEARCH & SUPPORT	Use of loose biomass for thermal applications, 500 kW thermal stratified downdraft gasifier, others	INDIA	Anil K. Rajvanshi	91 2166 22396 91 2166 23328	root@nimbkar.ernet.in
ONTARIO HYDRO (Environmental Responsibility and Leadership Dept.)	RESEARCH & SUPPORT	Support of Thermogenic 6 Mbtu/h gasifier & other renewable energy options	CANADA	John Russell	416 207 5684	
Pacific Northwest and Alaska Regional Biomass Energy Program	RESEARCH & SUPPORT	Regional biomass energy program of the US DOE	USA	Jeffrey James	206 553 2079 206 553 2200	jeffrey.james@hq.doe.gov
PARADOCS ENTERPRISES INC.	EQUIPMENT & CONSULTING	Project specific Engineering for renewable solid fuel energy systems	USA	Carol S. Stwalley, PhD, PE, Pres.	765 742 7438 765 420 7830	cstwalley@yahoo.com
PAUL SCHERRER INSTITUTE (PSI)	RESEARCH & SUPPORT	Bubbling fluidized bed research, research on Syn-fuel production from waste biomass	SWITZER-LAND	Luiz Carlos de Sousa C. Von Scala	41 56 310 40 60 41 56 310 21 99	desousa@psi.ch
POWER GASIFIERS INTERNATIONAL	GASIFIER SYSTEMS-LARGE	Complete gasificaiton systems, 40-5000kW	UK	Nigel Viney	44 767 680 351 44 767 683 298	

ORGANIZATION	CATEGORY	PURPOSE/DESCRIPTION	COUNTRY	CONTACT	PHONE/FAX	E-MAIL
POWER SOURCES, INC.	GASIFIER SYSTEMS-LARGE	Owner operator of Various commercial gasifiers for steam, hot air, power	USA	Dennis C. Williams	704 525 5819 704 527 1218	powersou@aol.com
PRIMENERGY, INC	GASIFIER SYSTEMS-LARGE	Multi zone, fixed grate, co-current Large gasifier systems for heat, steam power	USA	W. N. (Bill) Scott	918 835 1011 918 835 1058	sales@prmenergy.com
PRINCETON UNIVERSITY (Center for Energy and Env. Studies)	RESEARCH & SUPPORT	Evaluation of energy projects	USA	Eric D. Larson	609 258 4966 609 258 3661	elarson@princeton.edu
PRM ENERGY SYSTEMS, INC	GASIFIER SYSTEMS-LARGE	Multi zone, fixed grate, gasifier for process heat, steam, power.	USA	Ron Bailey Jr.,	501 767 2100 501 767 6968	info@prmenergy.com
PROLER INTERNATIONAL	GASIFIER SYSTEMS-LARGE	Reforming HC waste to syngas	USA	Dennis Caputo, VP	713 627 3737 713 627 2737	
PUROX	GASIFIER SYSTEMS-LARGE	Fixed bed updraft slagging gasifier for disposal of MSW, steam, syngas	USA	Hiroshi Tamura	415 345 1338	
PYNE	RESEARCH & SUPPORT	Pyrolysis/gasification newsletter	UK	Tony Bridgwater	44 121 359 3611 44 121 359 6814	a.v.bridgwater@aston.ac.uk
PYNE	RESEARCH & SUPPORT	Pyrolysis/gasification newsletter from Aston Univ.	UK	Tony Bridgwater	44 121 359 3611 44 121 359 6814	a.v. bridgwater@aston.ac.uk
QBEG LTD (Queensland Biomass Energy Group Ltd.)	GASIFIER SYSTEMS-LARGE	R&D & Commercialization of IGCC power cogen for sugar processing operations	AUSTRALIA	Terry Dixon	61 7 4952 7600 61 7 4952 1734	terry@sri.org.au
REGIONAL BIOMASS ENERGY PROGRAMS (U.S. Department of Energy, DOE)	RESEARCH & SUPPORT	Support of biomass power in U.S. in 5 geographical regions	USA	Mike Voorhies	202 586 1480 202 586 9815	michael.voorhies@hq.doe.gov
RENEWABLE ENERGY CORPORATION LTD. (REL)	GASIFIER SYSTEMS-LARGE	Manufacture Waterwide Close Coupled Gasifier for power through steam	AUSTRALIA	Christopher Uren	61 3 9820 1322 61 3 9820 5722	curen@renrg.com
SAO PAULO, UNIVERITY OF	RESEARCH & SUPPORT		BRAZIL	Suani T. Coelho	55 11 818 5064 55 11 818 5031	suani@iee.usp.br

ORGANIZATION	CATEGORY	PURPOSE/DESCRIPTION	COUNTRY	CONTACT	PHONE/FAX	E-MAIL
SARAGOSA, UNIVERSITY OF	RESEARCH & SUPPORT	Developing new fluidized bed gasification and gas clean-up processes/concepts	SPAIN	Prof. M. P. Aznar	34 76 76 13 39 34 76 76 21 42	
SHANDONG ENERGY RESEARCH INSTITUTE (SDERI)	RESEARCH & SUPPORT	Development of village gesifier system	CHINA	Xu Min	86 0531 296 5635 86 0531 296 1954	
SHERBROOKE, UNIVERSITY OF	RESEARCH & SUPPORT	University-driven research for fundamentals & training. Energy/Envir. centered research; 50 kg/h FB	CANADA	Prof. Esteban Chornet	819 821 7171 819 821 7955	echornet@coupal.gcm.usherb.ca
SINTEF (Foundation for Scientific and Industrial Research at the Norwegian Inst. Of Technology)	RESEARCH & SUPPORT	Research in gasification, pyrolysis	NORWAY	Morten Gronli	47 73 59 20 70 47 73 59 28 89	morten.gronli@termo.unit.no
SKYGAS VENTURESEARCH (Unitel)	GASIFIER SYSTEMS-LARGE	Electric Arc Fixed Bed Gasifier for Syn-gas, methanol	USA	Ravi Randhava, Serge Randhava	847 297 2265 847 297 1365	
SOFRESID/CALIQUA (Andco Torrax, Ascab-Stein)	GASIFIER SYSTEMS-LARGE	Slagging updraft air gasifier	FRANCE	M. J. Vigouroux	33 1 48 70 4692 33 1 48 70 4444	
SOUTHEASTERN REGIONAL BIOMASS ENERGY PROGRAM (SERBEP)	RESEARCH & SUPPORT	Regional biomass energy program of the US DOE	USA	Phillip Badger, Mgr	205 386 3086 205 386 2963	pcbadger@tva.gov
SRC-GAZEL (At UCL, Universite Catholique de Louvain)	GASIFIERS-SMALL	Pilot project for small scale power with short rotation coppice	BELGIUM	J. Martin (F. Bourgois)	32 10 47 2200 32 10 45 2692	bourgois@term.ucl.ac.be martin@te
STIRLING THERMAL MOTORS	EQUIPMENT & CONSULTING	Manufacturers of Stirling Engines	USA	William McKeough	314 458 0169 314 458 4937	
STWALLEY ENGINEERING (Division of Paradocs Enterprises,Inc.)	GASIFIERS-SMALL	Downdraft channel gasifier for ag waste gasification	USA	R. M. Stwalley		
SUNPOWER, INC.	EQUIPMENT & CONSULTING	Small scale power from biomass; free-piston, 2.5 kW Stirling engine	USA	Neill W. Lane	614 594 2221 614 593 7531	lane@sunpower.com

ORGANIZATION	CATEGORY	PURPOSE/DESCRIPTION	COUNTRY	CONTACT	PHONE/FAX	E-MAIL
SUR-LITE CORP.	GASIFIER SYSTEMS-LARGE	Fluidized Bed for Gas, Steam	USA	Edward G. Gjerde	562 693 0796 562 693 7564	sur-lite@deltanet.com
SUSTAINABLE ENGINE SYSTEMS (SES) LTD	EQUIPMENT & CONSULTING	Stirling engine development for biomass operation	UK	Drummond Hislop	44 71 792 2241 44 71 792 2543	
SWISS FEDERAL INSTITUTE OF TECHNOLOGY (ETH)	RESEARCH & SUPPORT	Support in Gasification	SWITZERLAND	Thomas Nussbaumer	41 1 632 2589 41 1 632 1176	nussbaumer@iet.mavt.ethz.ch
SYNGAS INC.	GASIFIERS-SMALL	Air/Oxygen fixed bed downdraft gasifier operated 1985-89 for power, syngas	USA	Tom Reed	303 278 0558 303 278 0560	reedtb@compuserve.com
SYSTEM JOHANSSON GAS PRODUCERS	GASIFIERS-SMALL	Downdraft low tar gasifier for power production, primarily from wood	SOUTH AFRICA	K. G. Johansson	27 11 310 1008 27 11 805 1138	
SYSTEM JOHANSSON GASPRODUCERS	GASIFIERS - SMALL	Tar free Power gasifiers - 350 kW	SOUTH AFRICA	Gus Johansson	27 11 310 1008 27 11 8051138	kgj@iafrica.net
T. R. MILES, TECHNICAL CONSULTING, INC.	EQUIPMENT & CONSULTING	Biomass Counciing, wide experience feeding, gasification, combustion wood, ag residues	USA	T. R. Miles	503 646 1198 503 605 0208	@teleport.com
TERAMETH INDUSTRIES (TMI)	GASIFIER SYSTEMS-LARGE	Landfill gas reforming to methanol, DME H2, CO2	USA	Gil Cervantez	510 939 2020 510 939 2052	
TERI (TATA ENERGY RESEARCH INSTITUTE)	RESEARCH & SUPPORT	Development of gasifiers forsilk boiling, drying, crematorium	INDIA	V. V. N. Kishore	91 11 462 2246 91 11 462 1770	vvnk@teri.ernet.in
TERMOQUIP ENERGIA ALTERNATIVA LTDA	GASIFIERS-SMALL	Downdraft gasifier	BRAZIL	Saul D'Avila	55 19 242 0371 55 19 242 0371	
THE BIOMASS ENERGY FOUNDATION	RESEARCH & SUPPORT	Downdraft gasification R&D, 25 kW Small Modular Biomass Power System	USA	Thomas B. Reed	303 278 0558 303 278 0560	reedtb2@cs.com
THERMOCHEM (MTCI)	GASIFIER SYSTEMS-LARGE	Pulse combustor steam fluidized bed	USA	Ravi R. Chandran	410 354 0420 410 354 0471	rchandran@mecionline.net
THERMOGENICS	GASIFIERS-SMALL	Bottom fed inverted downdraft gasifier, improved ESP cleaning for steam and power	USA	Stephen C. Brand	505 344 4846 505 344 6090	thermogenics@ADQ.com

ORGANIZATION	CATEGORY	PURPOSE/DESCRIPTION	COUNTRY	CONTACT	PHONE/FAX	E-MAIL
THERMOSELECT, SA	GASIFIER SYSTEMS-LARGE	Solid waste treatment; high temperature oxygen gasifier, turnkey plant	USA	David Runyon	248 689 3060 248 689 2878	
THIRD GENERATION LTD.	GASIFIERS - SMALL	Development of fully automated fixed grate gasifiers for heating	UK	Jonathan Taylor	44 1835 823043 44 1835 822997	admin@bblnorth.demon.co.uk
THOMAS KOCH ENERGI	RESEARCH & SUPPORT	Consulting on gasification of straw etc.	DENMARK	Thomas Koch	46 19 15 54 46 19 15 38	100711.220@compuserve.com
TPS TERMISKA PROCESSOR, AB (Formerly Studsvik, see Greve, BIG-CC, ARBRE)	GASIFIER SYSTEMS-LARGE	Major CFB gasifier manufacturer for IGCC, Greve plant in Chianti, IT, IGCC Brazil, UK	SWEDEN	Eric Rensfelt	46 155 22 13 00 46 155 26 30 52	tps@tps.se
UHDE GMBH	GASIFIER SYSTEMS-LARGE	Gasification of biomass, ceogeneration.	GERMANY	Jochen Keller	49 231 547 2335 49 231 547 3032	
ULSTER, UNIVERSITY OF, ENERGY RESEARCH CENTRE	RESEARCH & SUPPORT	Analysis of gasification, biomass, power plants	IRELAND	John T. McMullan		jt.mcmullan@ulst.ac.uk
UMSICHT (Fraunhofer-Institute for Environmental Safety and Energy Technology)	EQUIPMENT & CONSULTING	CFB gasification for gas engines	GERMANY	Markus Ising	49 208 8598 189 49 208 8598 290	info@umsicht.fhg.de
UMSICHT (FraunhoferInstitute for Environmental, Safety and Energy Technology)	RESEARCH & SUPPORT	R&D on 0.5 MW pilot plant; consulting for large scale gasifiers	GERMANY	Markus Ising	49 208 8598 189 49 208 8598 290	info@umsicht.fhg.de
VALMET AUTOMATON INC. (Energy product line)	EQUIPMENT & CONSULTING	Control and information management sstems for atmospheric and pressurized gasification eystems	FINLAND	Markku Tuovinen	358 3 268 8592FX	markku.tuovinen@valmet.com
VARNAMO IGCC PLANT, SYDKRAFT (Sydkraft, Foster Wheeler)	GASIFIER SYSTEMS-LARGE	IGCC, recirculating pressurized fluid bed for First biomass IGCC pressurized fluid bed plan operating.	SWEDEN	Krister Stahl	46 40 25 59 63 46 40 611 5184	

ORGANIZATION	CATEGORY	PURPOSE/DESCRIPTION	COUNTRY	CONTACT	PHONE/FAX	E-MAIL
VERENUM	RESEARCH & SUPPORT	Tar measurement, gas cleaning, water treatment	SWITZER-LAND	Thomas Nussbaumer	41 1 632 2589 41 1 632 1176	verenum@access.ch
VIENNA, TECHNICAL UNIVERSITY OF	RESEARCH & SUPPORT	Fluidized bed, dolomite catalysts	AUSTRIA	Reinhard Rauch	43 1 588 01 5130 43 1 588 01 587 63 94	hhofba@fbch.tuwien.ac.at
VOLUND R&D CENTER (Ansaldo)	GASIFIER SYSTEMS-LARGE	Updraft Gasifier for straw, wood-chips, heat, power	DENMARK	Knud E. Holm	45 75 56 8874 4575 56 8873	keh@ave.dk
VTT GASIFICATION R&D CENTER	RESEARCH & SUPPORT	Various gasifiers and bench rigs	FINLAND	E. Kurkela	358 9 456 6599 358 9 460 493	
WALES, UNIVERSITY OF(2)	RESEARCH & SUPPORT	200 kW fixed-bed/gas air heat exchanger for crop drying	UK	David Beedie	44 222 874 930 44 222 874 420	BeedieD@cardiff.ac.uk
WARREN & BAERG MFG. CO.	EQUIPMENT & CONSULTING	Manufacture cubing eqpt.	USA	Jim Pennington	207 591 6790 207 591 5728	
WASTE CONVERSION SYSTEMS	GASIFIERS-SMALL	Close coupled gasifier	USA	Stan Abrams	303 690 8300	
WELLMAN PROCESS ENGINEERING	GASIFIER SYSTEMS-LARGE	Updraft Fixed Bed Gasifier for generation of fuel & process gas from solid fuel	UK	Richard McLellan	44 121 601 3000 44 121 601 3123	wellman.process@dial.pipex.com
WESTERN REGIONAL BIOMASS ENERGY PROGRAM (WRBEP)	RESEARCH & SUPPORT	Regional biomass energy program of the US DOE	USA	Dave Waltzman	303 275 4821 303 275 4830	dave.waltzman@hq.doe.gov
WINROCK INTERNATIONAL	RESEARCH & SUPPORT	Support of gasification and biomass energy	WORLD	Dan Jantzen	303 422 7785	danjantzen@compuserve.com
WISCONSIN, STATE OF (Energy and Intergovernmental Relations)	RESEARCH & SUPPORT	Support of gasification	USA	Don Wichert	608 266 7312 608 267 6931	wichert@mail.state.wi.us
ZARAGOZA UNIVERSITY	RESEARCH & SUPPORT	Downdraft air gasification R&D, 22 & 200 kWe plants available; studies and expts on biomass and MSW	SPAIN	Pedro Garcia-Bacaicoa	34 976 761 880 34 976 761 861	bacaicoa@posta.unizar.es

CHAPTER 3

A DETAILED DESCRIPTION OF LARGE SCALE GASIFIER PROJECTS

CONTENTS

CHAPTER 3

DETAILED DESCRIPTION OF LARGE SCALE GASIFIER PROJECTS

INTRODUCTION:

In this chapter we discuss and review large scale gasifiers and gasifier systems (>10 MWe) and R&D work leading to large power gasifiers. It can be seen from the above list of gasifier projects and manufacturers that there is a great deal of activity. It would take many volumes to describe the activities of all the groups in detail. Some of the projects are just beginning and don't have much to report. Others are robust; still others are relatively inactive (or dead) and are included for historical perspective.

Many of the reports are based in part on a first hand visit (TBR) during a trip around the world in 1996, visiting gasification sites. Others are based on previous visits or early first hand information. We have also taken published reports from the literature of the 90s as a base for much of the description. In particular we have relied on the "Assessment of Thermochemical Conversion Systems" of Bridgwater & Evans [Bridgwater, 1993]; the recent survey of MSW gasifiers [Niessen, 1996] and the Minutes of the Large Scale Gasification Workshop [Kaltschmitt, 1996]. We have modified these according to telephone conversations or a site visit as indicated.

The data presented forms a basis for evaluating existing systems, but anyone seriously considering a particular system will have to contact the principles to find the current status of the project because these are ongoing, changing projects.

Sad to say, during the preparation of this book several of the projects have been abandoned, sometimes after the expenditure of 10s of millions of dollars. It is impossible to go back and rewrite each project. So some of this information will be of historical interest only, useful for a time when we decide to develop renewable energy in earnest. We have tried to add a note on the current status of each project at the end of each section.

Each gasifier system description is meant to stand alone and has its own specific sequence of figures and tables. Specific references are found at the end of each section.

GENERAL REFERENCES ON LARGE GASIFIERS

The following references on large gasifiers projects were found to be quite useful in this field.

[Bridgwater, 1993] Bridgwater, A. V. and Evans, G. D., "An Assessment of Thermochemical Conversion Systems for Processing Biomass and Refuse", Report, Energy Technology Support, (ETSU), ETSU B/T1/00207/REP, 1993.

[IGT, 1991] "Biomass Conversion: Thermal Gasification: Participating Countries Report", Report by IGT to IEA, 1991.

[Kaltschmitt, 1996] "Large-Scale Gasification Systems", Ed. Dinkelbach, L., (Minutes of the Joint workshop of the EU Concerted Action Committee on Gasification of Biomass held in Espoo, Finland, Sept. 26-29, 1996), publication of the European Union, International Energy Agency, 1996.

[Niessen, 1996] Niessen, W. R., Marks, C. H. and Sommerlad, R. E. "Evaluation of Gasification and Novel Thermal Processes for the Treatment of Municipal Solid Waste", Report NREL/TP-430-21612 by Camp Dresser and McKee, 1996.

DISCLAIMER

The information shown in these profiles is presented in good faith and is understood to fairly represent the technologies described at the time of compilation. Any errors or omissions are regretted but no responsibility can be accepted by the authors or sponsors.

3.1 BATTELLE COLUMBUS LABORATORIES, BCL

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Gasifier: Two-Fluid-Bed Pyrolyser-Combustor

Mark Paisley and Herman Feldmann at Battelle (Columbus) developed this process, the Battelle High Throughput Gasification System (BHTGS) starting in 1980, based on Battelle's extensive experience in coal gasification that goes back to 1929. The pyrolysis unit produces a very high energy gas (19-22 MJ/Nm^3) and charcoal. The charcoal is burned in a second fluidized bed to heat sand which is circulated back to the pyrolysis unit.

Mark Paisley has been in charge of the pilot reactor in Columbus for many years. He gave a summary of current status of both the research at Columbus and the 15 MWe plant in Burlington Vt. (see Burlington Electric) at the 4th Biomass of the Americas Conference in September, 1999.

PROCESS SUMMARY

Most of the processes discussed in this book react air directly with biomass to produce a low energy, <6 MJ/Nm^3, gas because of the nitrogen introduced with the air. A medium energy gas of 12 MJ/Nm^3 can be made using oxygen, but oxygen may cost $40/ton. The gas produced in pyrolysis typically is much higher in energy, 18-22 MJ/Nm^3 due to the presence of higher hydrocarbons , but only a third of the energy is in gaseous form and the gas is heavily loaded with large organic compounds (tars).

A double fluidized bed process was invented at Battelle, Columbus to circumvent this problem. Biomass is pyrolysed to medium energy gas in one bed. The charcoal is separated from the gas stream and burned with air in a second bed to heat sand which is returned to the first bed to supply the energy for pyrolysis. The tars in the gas are cracked over a catalyst, yielding a gas with 18.6-22.4 MJ/Nm^3 . Thus a cool, clean, medium heating value gas is obtained without the need for an oxygen plant. High feed throughputs of up to1000 $kg/h\text{-}m^2$ daf feed (wood) are attainable [Paisley, 1989].

Battelle has licensed this process to the Future Energy Resources Corporation, FERCO, in Atlanta. This process is now being scaled up to 15 MWe at the McNiel Power plant in Vermont. (See Burlington Electric).

DESCRIPTION

Background

The Battelle gasification system was developed under sponsorship by the US Department of Energy at the Battelle Columbus Laboratory. The present 254mm diameter plant project commenced in 1979 and construction was completed in 1980. The plant was operated until 1986. During 1988, RDF tests were conducted and about 8000 hours operating experience using RDF was gained. New tests have been carried out in the 1990s on a proprietary catalyst system.

Existing Process

A diagram of the 254mm diameter process research unit is shown in Figure 1 and process data are presented in Table 1. The endothermic gasification reactions are separated from the exothermic oxidation reactions resulting in the high heating value gas by using two separate reactors. Heat is transferred between the combustor and gasifier by circulating sand. Biomass is pneumatically transferred from a storage silo to the gasifier through a lock hopper system. Four metering feed screws transfer the biomass into a horizontal feed screw which transfers the feed to the bottom of a vertical feed screw . At the top of the vertical feed screw, the biomass falls by gravity into the bottom of the gasifier where it contacts incoming hot sand from the combustor . The feed/sand suspension is transported up through the gasifier

The gasifier is a 254mm (10inch) in diameter, 7m high steam blown recirculating fluidized bed reactor operating at atmospheric pressure and constructed from stainless steel fitted with 50mm of ceramic fiber insulation. The steam flow rate in the gasifier is constant to maintain a suitable fluidizing velocity. A commercial plant would be refractory lined. The gasifier is operated at temperatures between 600 and 1000°C. Temperatures below 600°C, are too low since the yields of gas fall to unacceptable levels.

Sand, char and product gas exit from the top of the gasifier and enter a cyclone mounted on top of the combustor which disengages the sand and char from the gaseous product and allows the solids to flow into the combustor by gravity . The combustor is a 1.02m (40 inches) diameter, 3.5m (11.5 feet) high, refractory lined, conventional fluidized bed gasifier which operates at approximately 1200°C. The combustor is started using a natural gas fired burner which can also be used to provide top up energy to the system when required such as during operation with bigh moisture content feeds and when high output operation is necessary. Hot sand is transferred from the bottom of the combustor to the gasifier via a conventional L-valve operated using nitrogen. The temperature differential between the gasifier and combustor is adjusted by altering the solids flow through the L-valve.

Exhaust gases from the combustor pass through a cyclone separator which discharges any entrained solids directly back into the FB combustor (Figure 1). The flue gases are cleaned and cooled using a venturi scrubber prior to discharge to atmosphere . Neither the gasifier or combustor reactors incorporate ash removal equipment although such systems would be incorporated into commercial scale plants to remove any tramp material.

Following removal of sand and char, the product gas passes through a second cyclone and is then cooled and scrubbed using water in a once-through spray tower and a-once through venturi

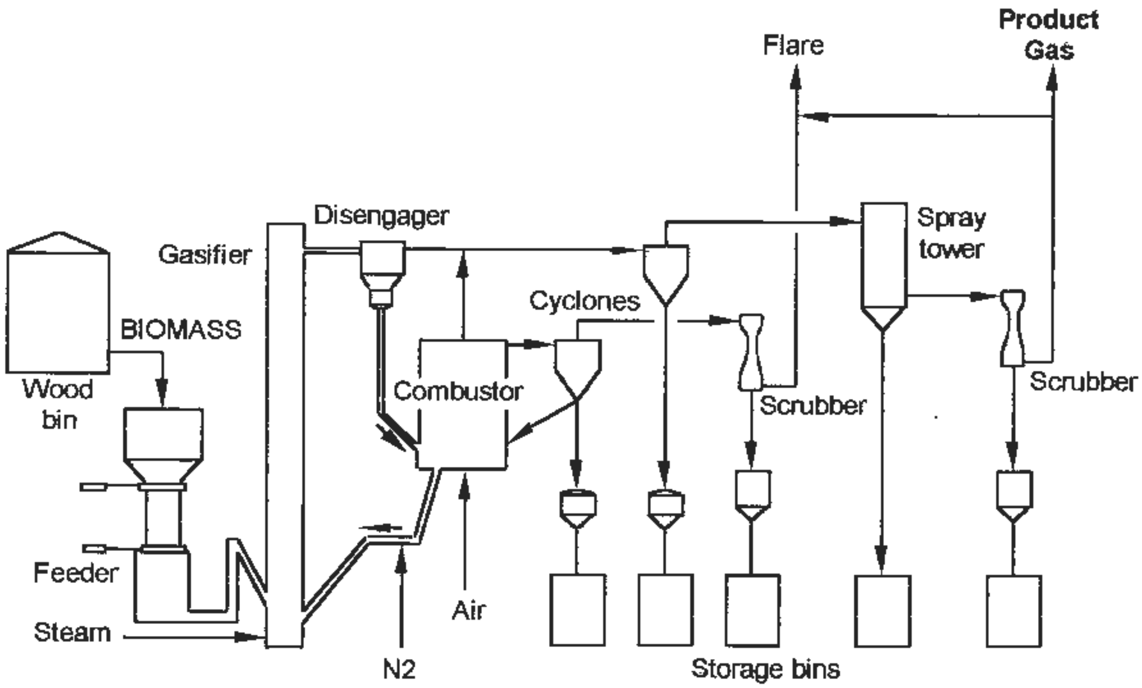

Figure 1 - Battelle Columbus Gasification System

Table 1 - Existing Process Data ,[Paisley, 1985],[Feldman, 1985]

Process Item	Gasification
Main feedstock	Woodchips, shredded stump material, RDF fluff ...
Main product	Fuel gas
Main product yield	75 % wt
Main product use	Fuel gas
Primary by-product	Char
Primary by-product yield	20 % wt
Primary by-product use	Process heating
Secondary by-product yield	5 %wt
Secondary by-product use	Process heating
Feedstock throughput (wood)	1000kg/h
Reactor type	Double Fluidized bed
Primary reactor operating pressure	1 bar
Primary reactor operating temperature	600-1000 °C
Gasifying agent	Air, steam
Air input rate	0.08 kg/kg dry feed
Steam input rate	0.31 kg/kg dry feed

scrubber (Figure 1). A small quantity of condensable organic material produced is easily separated from the scrubbing water . During operation, the scrubber becomes slightly acidic. The tars removed from the gas in the PRU are collected and burnt during startup. There is no flow of tars from the scrubber to the combustor although this might be incorporated in a commercial scale plant. The existing PRU water scrubber appears to operate satisfactorily. Other methods of gas cleaning are, however, under consideration. In a commercial system, the method of gas cleaning will depend on the product gas application. Following gas analysis, the product gas from the PRU is flared.

In addition to the 254mm diameter PRU system installed at Battelle, a second 50mm diameter reactor system has now been installed.

FEEDSTOCKS AND CHARACTERISATION

The feedstocks which have been tested are listed in Table 1. Little feed preparation is required beyond that required for efficient feed handling. There is no change in system performance with changes in feedstock [Feldman, 1985]. The maximum acceptable moisture content is 38% (wet basis) while the mean feed moisture content is 10% (dry basis). Increased feed moisture content increases the system energy requirement. The maximum acceptable feed ash content (daf basis) is 20% while the mean ash content of the wood tested is 1% (daf basis) [Paisley, 1985]. Tests were conducted using a mixture of poplar and a straw type feed (cut into 50mm strips). Approximately 30 hours operational experience had been gained using this feed.

The wood chip size used in another 254mm PRU plant was approximately 25x25x6mm while the bark tested was in the form of 305mm strips. The bark did not cause feed handling problems and due to rapid reaction time in the gasifier, did not foul in the fluidized bed gasifier. A commercial scale plant would use wood chips with a characteristic size of approximately 50mm. This limitation is set hy the feed handling system and not the gasification system. The gasification system performance is relatively independent of feed particle size.

RDF fluff was tested in 1988. However, the feed throughput relative to that of wood was reduced to approximately 225 kg/h due to the lower bulk density of RDF fluff compared to wood. There is only limited experience of using RDF feed and the process has not yet been optimized for RDF operation. RDF handling was not found to cause any difficulties.

PRODUCTS

Gas Characteristics

The composition and characteristics of the dry product gas are presented in Table 2. The raw gas composition is not reported. The product gas has a high energy density compared with the product gases from air blown gasifiers due to the separation of the gasification and combustion steps.

Currently, the tar removal efficiency is not very high leading to a final product gas tar content of about 2% by mass of the dry wood feed. Chlorine and sulfur from the fuel will remain in the product gas and hence the flue gas from the product gas application (before flue gas cleaning). The levels of chlorine and sulfur in the product gas will depend on the feed and the type and extent of product gas cleaning.

Liquid Products Characteristics

The Battelle gasifier produces 0.05 kg/kg daf feed tar which are burnt in the combustor at startup. Approximately 0.20 kg/kg daf feed of char is produced which, when separated from the product gas, is burnt in the combustor to produce heat for gasification.

Table 2 - Summary of Dry Gas Characteristics (Gasification of Wood) [Paisley, 1985]

Gas composition	, % volume
Hydrogen	14.9
Carbon monoxide	46.5
Carbon dioxide	14.6
Methane	17.8
C_2+	6.2
O_2, N_2, Cl2, S, H_2O	0
Gas rate (dry)	0.8 Nm^3/kg *
Gas exit temperature from gasifier	820°C
Heating value	18.0 MJ/Nm^3

PERFORMANCE

The overall process thermal efficiency (undefined) with a wood feed is 72% [Paisley, 1985]. The product yield (wood feed) is 0.75 kg/kg daf feed (0.8 Nm^3/kg) [Paisley, 1985]. By altering process conditions such as the gasification temperature, however, process yields can be changed. Gas yields of up to 0.95 kg/kg daf feed are possible although at this conversion level, there is insufficient char production for the production of heat for gasification and the system is said to be out of balance [Feldman, 1985]. There is little variation in the yields shown as a result of varying the feedstock.

The highest turndown ratio achieved using the 254mm pilot plant was approximately 10:1. Generally, however, the turndown ratio is approximately 5:1. It is estimated tbat a commercial plant would have a turn down ratio of approximately 4 or 5 to 1.

The high throughputs obtained during wood gasification could not be obtained for RDF gasification. Performance data for the gasifier operating using RDF is available .

EMISSIONS

The by-product production from this process is low resulting in simple environmental control systems. The primary gaseous emissions for consideration from this plant are carbon dioxide, particulates and fly-ash. It is estimated that a bag house filter would be sufficient to trap the particulates and fly ash.

COSTS

Operating Costs

The cost of wood, bark and sawdust in September 1985 was estimated to be $25 /daf ton. Costs of other feeds and services are not reported [Paisley, 1985].

Product or Production Costs

The estimated product gas cost in September 1985 was $3.54/GJ (wood feed) [Paisley, 1985].

The Battelle gasification system being omnivorous could be used to produce, from a number of waste materials, a medium heating value fuel gas for use as a boiler fuel or, in combination with an engine or gas turbine, power. Due to the consistently high higher heating value gas, the product gas from this system can be used in gas turbines designed for natural gas [Paisley, 1985B].

The minimum acceptable commercial size system which could be built is approximately 200 ton/day. At lower throughputs, the percentage heat loss (percentage of wood input) is estimated to become unacceptably high. The maximum acceptable size is limited by feed accessibility. It would be possible, therefore, that the largest plant fueled by MSW would be larger than the largest plant fueled by wood.

Exploitation of tbe technology would be by license to an outside manufacturing company.

CURRENT STATUS AND FUTURE PLANS

The 254mm diameter gasification system is currently operational and has been used to test the NREL molecular beam mass spectrometer. The system is available for tests relevant to the scaled up version now being tested at the McNeil Power plant in Burlington, Vermont. During the current program, a more complete gas analysis (raw gas) is being made in preparation for the future use of a catalytic tar cracking reactor. The catalytic reactor will comprise a (classic) fluidized bed (using nickel) to remove tars and improve the gas quality. A new catalyst is being investigated.

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3.2 BIOSYN

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Process: Fluidized bed for methanol production

HISTORY

The history of the BIOSYN project and gasifier are included here because they represent a major effort that succeeded technically, but failed in the 1980s for economic reasons. The following details were supplied by Prof. Esteban Chornet at Sberbrooke University [Chornet, 1998]. (See Sherbrooke Univ.)

In the early 1970's CIL, a wholly owned Canadian subsidiary of ICI, initiated an environmental program to develop versatile fluid bed technology to convert its industrial wastes into useful syngas for either synthesis or energy. A pilot plant was erected in Kingston, Ont. The project was known as OMNIFUEL. Three engineers were in charge: John Black, Keith Bircher and John Chisholm. The process is hased on the John Black U.S. Patent No. 4,968,325.

CIL restructured and discontinued its project. The three engineers formed their own company, BBC engineering, and installed a demonstration gasifier (10 tons/h) coupled to a boiler at the Levesque sawmill in Hearts, Ont. The demonstration lasted for three years. It was a technical success but the economics did not favor commercialization in the mid 1980s.

In the late 1970's Canertech, ithe Canadian federal company created to promote alternate energy sources, and Nouveler, a HydroQuehec subsidiary in charge of novel energy alternatives, formed a joint venture, Biosyn Inc., whose mission was to demonstrate the gasification of biomass residues and the conversion of the syngas to methanol. The project was structured in 1980 with a capital of 22 MM$ Can. Phase I of the project was to design, huild and operate the gasification section of the plant. SNC, a major Montreal-based engineering firm, and BBC engineering were retained to design and erect the demonstration plant to treat 10 tons/h of forest residues. The gasifier was to he pressurized (16 bar). The plant was constructed at St. Juste de la Bretenniere, Que., in the period 1981 - 84. Biosyn Inc., hecame the operator with a staff of 16 persons. A technical advisory committee was formed to lead the technical aspects of the project. R.P. Overend, M. Bergougnou, J. Grace, A. Chamberland and E. Chornet were the members of the committee while J. Black acted as consultant. A strong research effort was carried out in parallel at IREQ, the research arm of HydroQuebec.

The demonstration proceeded between 1984 and 1986. **Over 1600 h** of operation were accumulated using various gasification regimes and feedstocks. Coupling the gasifier to a 750

KVA Alsthom diesel generator was achieved for a period of over 600 h. At the corporate level, Canertech was dissolved in 1984, due to a change of government, and Nouveler became the only shareholder of Biosyn Inc.

In the mid-1980's a joint venture between Nouveler and SNC was formed, **Biodev Inc.**, to commercialize the Biosyn technology. Biodev Inc., led by G. Drouin obtained a license to the Biosyn know-how and secured a demonstration project in French Guyana. The project was financed by Electricite de France and was supposed to produce 7.5 MW of electricity. The plant was constructed and briefly operated but cost overruns and higher-than-expected operating costs made the economics difficult. The project was abandoned in the late 1980's. Biodev was also dismantled and G. Drouin formed an independent company, Biothermica Ltd., to pursue the commercialization effort of both the gasifier and of hot gas cleaning technology. The license obtained by Biodev was transferred to **Biothermica**, who still holds the license today.

The Biosyn demonstration at St. Juste was satisfactorily completed in 1987. The information obtained allowed a thorough assessment of costs. It became clear that the return of energy prices to the pre-1973 level would make impossible a methanol plant from biomass-derived syngas. HydroQuebec, who disposed of a production capacity of 30,000 MW mainly very low cost hydroelectricity, did not see any advantage to produce electricity by coupling the gasifier to a gas turbine, an obvious technical choice. In 1988, HydroQuebec decided to discontinue Biosyn Inc. The assets were sold to a sawmill company, **BECESCO**, in 1989. The St. Juste facility was operated since as a typical sawmill with the gasifier still erected as a "monument to technology".

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3.3 Burlington Electric (FERCO, Battelle)

Process: Double Fluid Bed Pyrolytic Gasification Integrated Gasifier Combined Cycle Power Plant

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IGCC Demonstration of Battelle gasifier at existing wood plant

Other Contacts: Mark Paisley, developer of the gasifier at Battelle, 614 424 4985; The Farris brothers, FERCO (Future Energy Resources Company), 404 612 5575, the licensees and commercializers of the gasifier. Milton is chairman of the board and Glenn has worked with NREL. Zurn/NEPCO is in charge of engineering and construction (Joe Sapp, 207 791 5112; 5000 general). Susan Moon at NREL is their contact, 303 278 0560; Fax 303 275 3619.

RECENT EXPERIENCE

Mark Paisley reported at the 4th Biomass of the Americas Conference in September 1999 that the plant achieved full steam gasification, energy transfer with hot sand, self sustaining process operation and they supplied 80 M Btu to the McNeil Power plant in late August, 1999. We have chosen this plant for the cover on our hook hecause it isone of the most technologically advanced in the U.S. and has been in development since 1980.

HISTORY

Over the past 15 years Battelle (Columbus) has developed a Double Fluid Bed Pyrolytic Gasification unit that produces gas with 18-22 MJ/Nm^3 without using oxygen. Biomass is pyrolysed in one fluid bed without oxygen, yielding gas, charcoal and organic compounds. The charcoal and sand are separated in a cyclone and fed to a fluid bed combustor that burns the charcoal, reheating the sand to 1000-1050°C. The hot sand is then fed back to the first combustor to provide the heat of pyrolysis, as shown in Fig. 1. A layout diagram of the plant is shown in Fig. 2.

In 1984 Burlington Electric commissioned the world's largest wood power plant, using 85 tons/h to generate 50 MWe of power. The McNeil plant relies on the abundant wood supply of Vermont (80% forest cover). The plant has continued in operation. Even though it can burn gas or oil as well, depending on prices, it still burns wood much of the time. Politically the plant and the new project are supported by state officials and Senator Patrick Leahy.

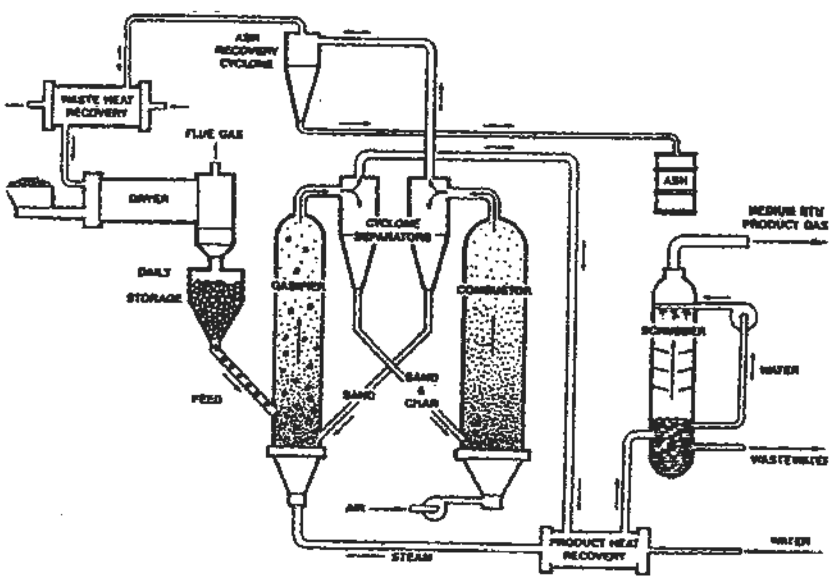

Figure 1 - Diagram of Burlington fluidized bed gasifier system for production of medium energy gas without an oxygen plant

GAS CLEANUP

Battelle has developed a catalyst, DN-34 for conditioning the gas at the McNeil site. NREL worked with Battelle in the testing of the catalyst using the transportable molecular beam mass spectro meter, TMBMS.

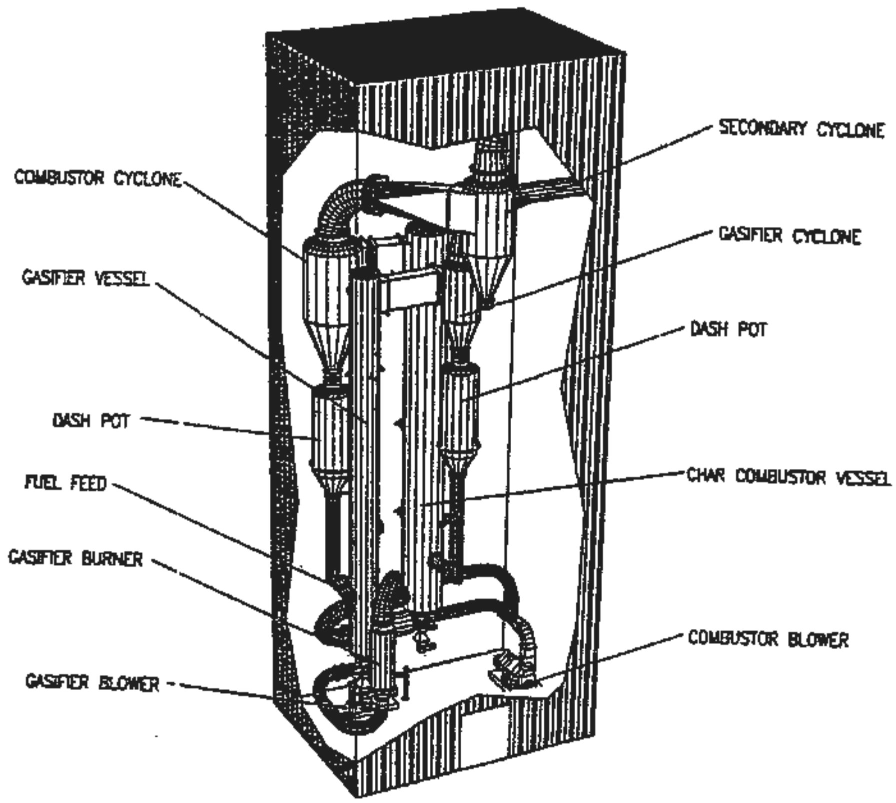

Figure 2 – Layout of Burlington Electric Double Fluid Bed pyrolytic Gasification System

CURRENT STATUS

In an Email dated 5/6/99 John Irving, the McNeil Plant Manager (jirving104@aol.com) said "The Vermont Gasification Project first produced gas in February, 1998. It is located on the site of an existing 50 Mwe combustion biomass plant that has been operating commercially since 1984. The gasifier project has been in the process of shakedown and startup. There are several significant modifications that were deemed necessary to tht eoriginal design to improve reliability and operation. The most significant of these changes is a major modification to the product gas cooling system which is being installed currently. The plant is scheduled to return to service in mid-June."

3.4 Carbona Inc. (formerly Enviropower, and Vattenfall*)

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In the beginning of 1996 former employees of Enviropower Inc. (owned by Tampella Power and Vattenfall) acquired through a management buyout the rights to Enviropower's fluidized bed gasification technology and formed the new company, Carbona Inc. to continue gasification activities. They will offer gasification based power plants for coal and biomass. They are continuing the activities in three locations; Tampere and Helsinki in Finland and Atlanta in the U.S. [Kaltschmitt, 1996]

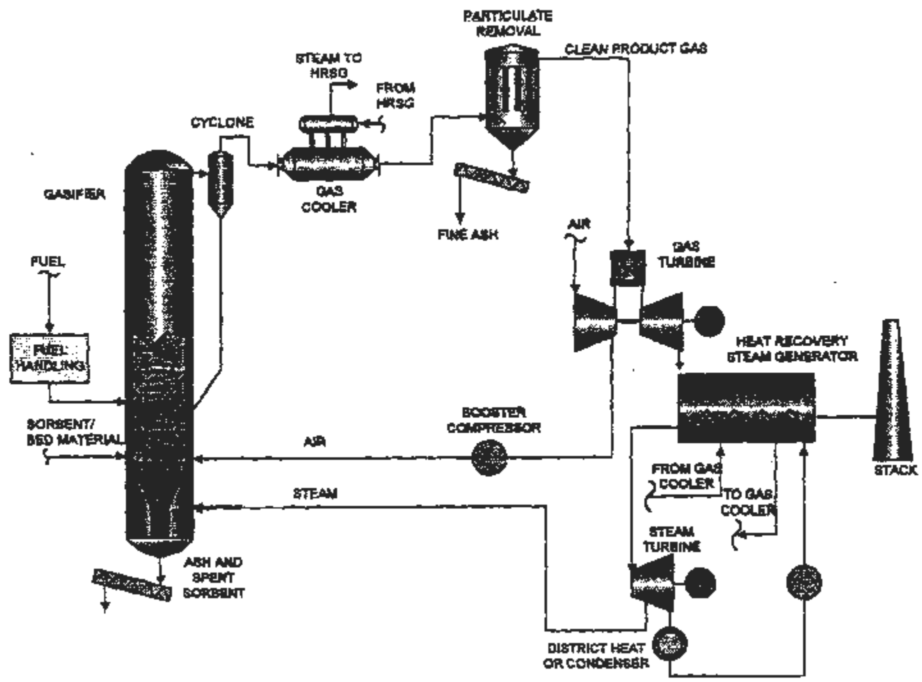

Fig. 1 Carbona Pressurized Fluidized Bed Gasifier (I will use your figures here)

On Sept. 28, 1996 the members of the IEA Gasification workshop paid a visit to the fluidized bed plant in Tampere, Finland, about 80 miles North of Helsinki. The gasifier is shown in Fig. 1. The gasifier uses the IGT U gas - Enviropower technology. It is an air blown fluidized bed gasifier 60 cm ID X 20 m tall, with hot gas cleanup operating at a maximum of 30 Bar, 15-20 MWth and consumes 100 tons/day of biomass with 10-50% moisture. Dolomite or sand are used as a bed material. The gasifier operates at 800-1000°C, the cleanup at 400-650°C. It uses ceramic candles for gas cleanup. The heat is currently used for district heating in the city.

There have been 24 test runs on the gasifier so far using biomass, coal, lignite, straw, papermill residues and energy farm short rotation willow. The gasifier has run a total of 1600 hours burning 5100 tons of materials.

Carbona is also working on other gasifier types; downdraft fixed bed gasifiers for 0.1-0.5 MWe and small fluidized beds for 0.5-5.0 MWe power generation with reciprocating engines; and IGCC to be used in gas/steam turbine power generation. They currently are working on three major orders. They are working with Ignifluid Boilers India Ltd. to build an IGCC 55 MW power plant using brown coal. ($70M). Plant construction has started and should provide electricity in the summer of 1997, but will be run initially on naphtha.

A 75MW IGCC power plant project is being planned for Minnesota costing about $200M, partly funded by the US. DOE. Westinghouse will deliver the gas and steam turbine plant.

In Finland the city of Kotka has started an 8 MW wood based IGCC project using Carbona technology with financing from the Finish Ministry of Trade and Industrie and from the Thermie program of the European Union. It will use the existing power plant and should be operative in 1999.

Carbona is an example of bow a small company from a small country can be a part of large world-wide projects using corporate partners from around the world.

GENEALOGY:

Enviropower is a subsidiary of former Tampella Power, Inc. - now Kvaerner Pulping Inc. - and Swedish Vattenfall AB. Enviropower was established in 1989 to develop gasification technology. Enviropower's operations were ceased due to ownership cbanges in Tampella Power. The rights to Enviropower's know-how were acquired by some of its management, who formed Carbona Inc. Carbona has 15 former key Enviropower employees. The company bas a subsidiary in Atlanta, USA.

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3.5 Elsam/Elkraft

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Process: Gasification of Biomass and Coal for Power Production in Denmark

BACKGROUND

More than 90% of the fuel for power production in Denmark is coal. With a growing political interest in utilizing biomass as fuel for power production and a wish for reduction in CO2-emission, the Danish utility groups ELSAM and ELKRAFT in 1992 launched a large R&D program targeted at the implementation of biomass for power production. These projects cover:

- **Assessment of biomass resources (amounts available, costs, handling, logistics, characterization)**

- **Combustion of biomass in central power stations**
- **Utilization of biomass in local CGP plants (combustion, gasification, pyrolysis)**
- **Combined gasification of coal and straw**

An R&D project including a comprehensive test gasification program. The aim of the project was to:

- **Initiate the development of technology for combined gasification of coal and straw in large-scale combined heat and power plants**
- **Evaluate the properties and behavior of complete plants based on gasification of coal and straw**
- **Perform test gasification of coal and straw at existing test plants.**

To achieve this, co-gasification tests with coal and straw were carried out in both pressurized fluid bed and entrained flow gasifiers. Test gasification with coal and straw have been performed in laboratory reactors (Risø, Denmark), in a 3 MW pressurized entrained flow gasifier (NOELL, Germany) and in 0.3 MW and 15 MW fluidized bed gasifiers (VTT and Enviropower, Finland).

During the tests, a matrix of fuel types, coal/straw ratios and process parameters were explored. Information on operational experience, gas compositions, gas contaminants and residual products were collected.

Handling, pretreatment and feeding of straw have been investigated as part of the gasification tests and in separate studies covering energy consumption for milling, pressurizing, physical characterization of straw and through specific feeding tests.

Based on test results and a bot gas cleaning study a computerized flowsheet model for IGCC plants has been developed and overall plant performance on coal/straw mixtures has been evaluated.

The project was initiated in January 1992 and completed in June 1995 with financial support from the European Commission under the APAS Clean Coal Technology Program.

3.6 Enviropower (Vattenfall, Tampella, IGT)

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Gerth Karlsson, Project manager ENVIROPOWER INC. Vattenfall Utveckling AB

PROCESS FOR LARGE, CENTRAL POWER PLANTS - BIOMASS IGCC

Enviropower, a joint venture company between Vattenfall and Tampella Power is developing the simplified Integrated Gasification Combined Cycle (IGCC) based on pressurized fluidized bed gasification applying air-blown gasifier and an advanced hot gas cleanup. This technology provides the advantage of high power generation efficiency, a high power-to-heat ratio, excellent environmental performance, simple plant design and modularity. The gasification concept was originally developed by the Institute of Gas Technology (IGT - see below) Chicago, USA and has been further developed by Enviropower.

The Biomass IGCC concept includes a fuel dryer, a pressurized fuel feeding system, an air blown gasifier with gas cleaning system and a gas turbine integrated with the gasifier. Enviropower's plant design allows the use of variety of feedstocks - different types of biomass and coal - alone or in combination. Wet fuels like biomass must be dried to 20-30 % moisture content. A study of three different steam dryers has been conducted. The aim was to study the technical function of steam dryers for drying of biomass and to give a basis for estimation of performance data.

An extensive gasification research and development program is underway. A 15 MWtb capacity gasification pilot plant was built for research, development and component testing of the gasification and bot gas cleanup processes. The gasifier operates up to 30 bar and 1100 °C. The main objectives of tbe biomass gasification test program using air-blown gasification and hot gas cleanup was to verify and demonstrate the ability of the gasifier process and hot gas cleanup system under commercial scale IGCC plant operating conditions. The pilot plant includes a lock-hopper feeding system which was operated successfully with different types of fuels like forest residue, wood chips, dried/wet lignite, dried/wet coal and straw mixture as well as with paper mill residue consisting bark, sludge and paper.

Gas turbine combustion tests were also conducted. The main purpose was to verify that the span of possible product gas compositions from the gasifier can be combusted in the combustion system of the gas turbine and to investigate gaseous emissions of environmental concern. The gas turbine combustor selected for the testing proved to well suited for biomass applications. The combustion technology will develop rapidly in the near future

The high efficiency of electricity production and the excellent environmental performance will make IGCC competitive compared to conventional power plant technologies. The main issue is to keep the specific investment cost low and to maximize the efficiency and environmental performance. The right component selection and integration of drying, gasification, gas turbine, and steam process are the key questions in IGCC design. The economical calculations show that the IGCC plant size must be large enough to demonstrate the benefits of the new technology. The results will be presented in Finnish conditions where the feasibility limit seems to be in the 20-30 MWe size class.

Biomass availability is also viewed. The most realistic potential seems to be in the countries where biomass waste is generated by large industrial sites using biomass as raw material such as pulp and paper mills and sugar industries.

3.7 Foster Wheeler – Pyroflow (Formerly Ahlström Corporation)

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Process: Circulating Fluidized Bed Gasifier

PROCESS SUMMARY

Foster Wheeler manufactures both atmospheric (Pyroflow) and pressurised fluidized bed gasifiers. Feeds tested in the atmospheric gasification system include wood, bark, peat, lignite and coal. The approximate minimum and maximum feed throughputs for the atmospheric system were 2000 kg/h and 27000 kg/h (daf feed) respectively [Nieminen, 1985]. A pilot scale atmospheric gasifier exists but is currently not in use (April 1992) [Lundquist, 1992]. Most of the information contained here is from [Bridgwater, 1993].

Current research is directed towards pressurized gasification in cooperation with Sydkraft (a Swedish Utility) [Lundquist, 1992]. Construction of a demonstration scale IGCC gasifier at Värnamo commenced in September 1991 [Anon, 1984]. (See Varnamo, below) The objectives of the Värnamo project were to demonstrate the technology and to determine the costs of operating and maintaining commercial scale plants as well as to provide a basis for the evaluation of the likely capital costs of future plants [Anon, 1984].

This report will cover the atmospheric pressure gasifier.

BACKGROUND

Foster Wheeler is a commercial company manufacturing boilers and gasifiers with approximately 12 years experience of gasification technology [Nieminen, 1985]. In 1990, group net sales were US$2300 x$10^6$ and the group employed 12000 people. Foster Wheeler Pyropower headquarters were located in San Diego, California, USA. Foster Wheeler Boilers were based in Varkaus, Finland. Equipment manufacture for the USA market is subcontracted and equipment for the European market is manufactured in Varkaus.

As of June 1992, 10 bubbling fluidized bed combustion installations, 72 Pyroflow CFB combustion installations were in operation and 28 Pyroflow CFB combustion units were under construction. Over 250 years total operating experience of combustion has been accumulated. The capacities of the installed combustion plants range from 3 to 313 MW_{th} and the feedstocks used include peat, wood waste, peat, oil, bark, brown coal, coal water mixture, coke, petroleum, oil shale and wood chips.

Six atmospheric pressure gasifiers (3-35 MW_{th}) have been installed between 1982 and 1986 in Finland, Sweden and Portugal [Nieminen, 1985]. Four of these gasifiers were known to be operational as of June 1992.

ATMOSPHERIC GASIFICATION SYSTEM

PILOT PLANT

Gasification research is carried out in Karhula, Finland (56 employees). One pilot scale atmospheric gasification plant ($3MW_{th}$) is installed at Karhula. This pilot plant is currently not operational but is complete and could he operational within two months. The last pilot plant test was conducted in 1987. Typical process data are given in Table 1.

The Pyroflow gasifier is an atmospheric circulating fluidized bed gasifier operating at 800-1000°C and is based on the design of the Pyroflow boiler [Niessen, 1996]. It was developed for lime kiln applications.

Power production was not investigated although the product gas from a wood fueled atmospheric gasifier has been used following water scrubbing to fuel a diesel engine (engine size: 404 kW/cylinder). The product gas was scrubbed in a pre-scrubber which cooled tbe gas from 200°C to 60°C and removed between 30 and 50% of the tars. The gas was subsequently scrubbed using a venturi scrubber which removed 96-97% of the remaining tars. The total tar removal efficiency is 98.6%. The overall efficiency to electricity was 39.5% at MCR. Currently, Foster Wheeler would suggest that the pressurized gasification system being developed for Värnamo (see below) should be used for electric power generation from biomass.

Table 1 - Existing Process Data - Pilot Plant

ITEM		UNITS
Main product yield	3.27	kg/kg daf feed
Main product use	Flare	
Feedstock throughput (daf)	600	kg/h
Reactor type	Circulating fluidized bed	
Primary reactor operating pressure	1	bar
Primary reactor operating temperature	905	°C
Reactant	air	
Reactant input rate	1.70	kg/kg daf feed
Liquid waste flowrate (tars)	0-10000	mg/Nm^3 gas

The Pyroflow gasifier consists of a vertical cylinder and a cyclone both lined with refractory. Biofuel is fed to the pilot gasifier (height ~11m, ID ~0.6m) using a screw feeder mounted at a position above the grate where there is a relatively high upward gas velocity (4-10 m/s) and there is no oxygen present. Sand is added to the feed to make up bed losses and gas ingress to the feeding system is prevented by injecting air into the feeding system.

The fine fuel particles are entrained with the gas flow where they dry and pyrolyse. High temperatures in this feeding region convert the volatiles released by pyrolysis to gas. The gas-fuel suspension exits the gasifier vessel and enters a cyclone which separates the solid particles (sand, char and ash) from the product gas. The cyclone separates 99% of the solids from the gas. The separated particles are recycled to the bottom of the gasifier through a downcomer pipe where the char is producing the heat required for gasification. Tar formation is minimal as the gasification reactions take place very rapidly and at high temperature. The product gases following the cyclone contain no particulates greater than 100μm in size. Finally the product gas produced hy the pilot plant is flared.

Ash is removed from the base of the gasifier. Input air to the gasifier is preheated by product gases to approximately 400°C prior to entry to the gasifier. The pilot gasifier contains in-bed cooling tubes to permit gasifier temperature control. (This feature is not incorporated in commercial plants.)

The type of feed pretreatment technology necessary for a commercial plant will depend on the raw feed characteristics.

COMMERCIAL ATMOSPHERIC GASIFICATION SYSTEM

An example of an installed commercial scale atmospheric gasification plant (Wilh. Schauman's mills at Pietarsaari, Finland) is shown in Figure 1. This plant produces a low heating value gas from waste wood for firing a lime kiln and was first operated in 1983[Niessen, 1996].

Feedstocks and Characterization

Wood, bark, sawdust, peat, lignite and coal have been tested [Nieminen, 1985]. The Pyroflow gasifier can also gasify waste water sludge from wood processing plants [Niessen, 1996]. RDF is not currently considered a good fuel for this system due to undeveloped feeding systems and the potential for corrosion due to the chlorine content.

Feed particles less than 10mm are acceptable. The mean size is approximately 2-4mm. The feed moisture content should he less than 70% (basis not reported) [Nieminen, 1985]. The feed higher heating value is normally between 15 and 25 MJ/kg daf [Nieminen, 1985]. There are no limitations to the feed ash content [Nieminen, 1985].

Gas Characteristics

The product of this process is a fuel gas which can be used for a number of applications including lime kiln firing [Niessen, 1996]. The product gas quality will depend on the feed characteristics and quality and the gasification conditions [Nieminen, 1985]. The gas contains no sulfur and is easy to clean as most of the ash is removed during the gasification stage [Niessen, 1996]. Details are given in Table 2.

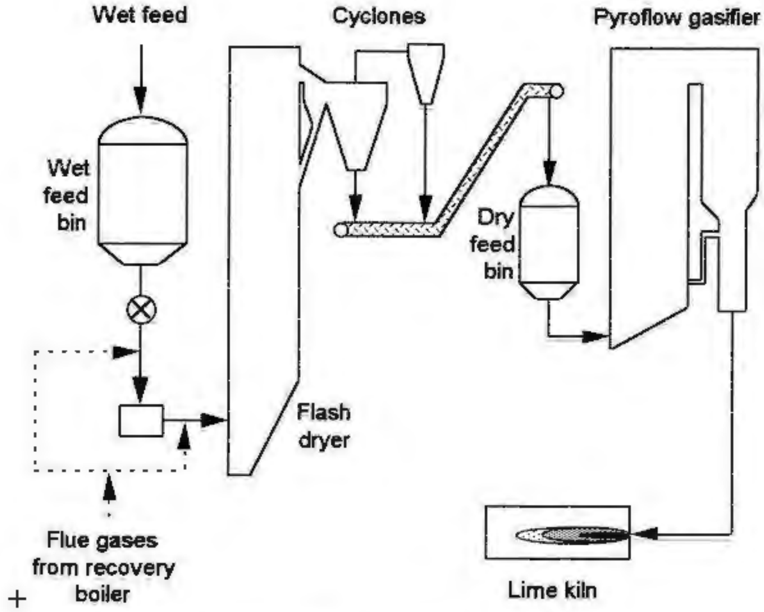

Figure 1 – Foster Wheeler Gasifier System

Table 2 - Summary of Gas Characteristics (Wood Gasification)

Gas	% volume (dry)
Hydrogen	15-16
Carbon Monoxide	21-22
Carbon dioxide	10-11
Methane	5-6
Nitrogen	46-47
Sulfur	0
H_2O	0
Gas output rate (dry)	1181 Nm^3/h
Gas exit temperature	700 °C
Heating value	7.5 kJ/Nm^3

Performance

The highest cold gas efficiency reported for the pilot plant is 79% and the claimed turn-down ratio is 4:1 [Nieminen, 1985]. The gas yield is shown in Table 1. A representative energy balance is shown in Table 3.

Table 3 - Atmospheric Gasification Plant - Representative Energy Balance

Inputs	MW
Feed	3.10
Outputs, MW	
Chemical energy of gas	2.46
Sensible energy of gas	0.44
Chemical energy of char	0.06
Heat losses	0.14
Total	3.10
Closure, %	100.0
Cold gas efficiency, %	79

Process Costs

Gasification plants are made to order and process costs are not reported. Process costs will depend on the feed conditions, local situation, type of fuel, extent of gas clean-up, size of plant etc.

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3.8 Institute of Gas Technology

Fluidized Bed Gasification - Renugas Process Pilot Scale Gasifier

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PROCESS: Pressurized Fluid Bed tests on Renugas system; Processes for Power, Methanol

In April, 1996 I visited the IGT energy park in South Chicago and was taken on a tour of the gasifier facilities by Mr. Mike Onischak. The Renugas process was developed in 1979, modifying the U-gas coal process to take advantage of the higher reactivity of biomass. The Renugas technology has been licensed, on the basis of tests at this Chicago facility, to Tampella and to the Biomass Gasification Facility (BGF), now under the direction of Westinghouse in Hawaii. (See Tampella, BGF). The Hawaii project has now been abandoned (1999) and is being dismantled. However, the experience gained both at IGT and Hawaii may be valuable in the future.

The Institute of Gas Technology, IGT, is a not-for-profit research, development and educational institute with approximately 18 years experience in biomass gasification technology [Lundquist, 1992]. They do work in fields of interest to the natural gas and power industries.

PROCESS SUMMARY

The aim of this process is the gasification of biomass in a pilot scale 11 tonne/day, pressurized single-stage, oxygen blown fluidized bed gasifier to produce medium heating value gas suitable as an industrial fuel gas, or for upgrading to substitute natural gas or synthesis gas. The gasifier can be operated either air or oxygen blown, at pressures up to 32.7 bar and at temperatures between 850°C and 900°C. The first demonstration scale gasifier is currently under construction [Bridgwater, 1993].

DESCRIPTION

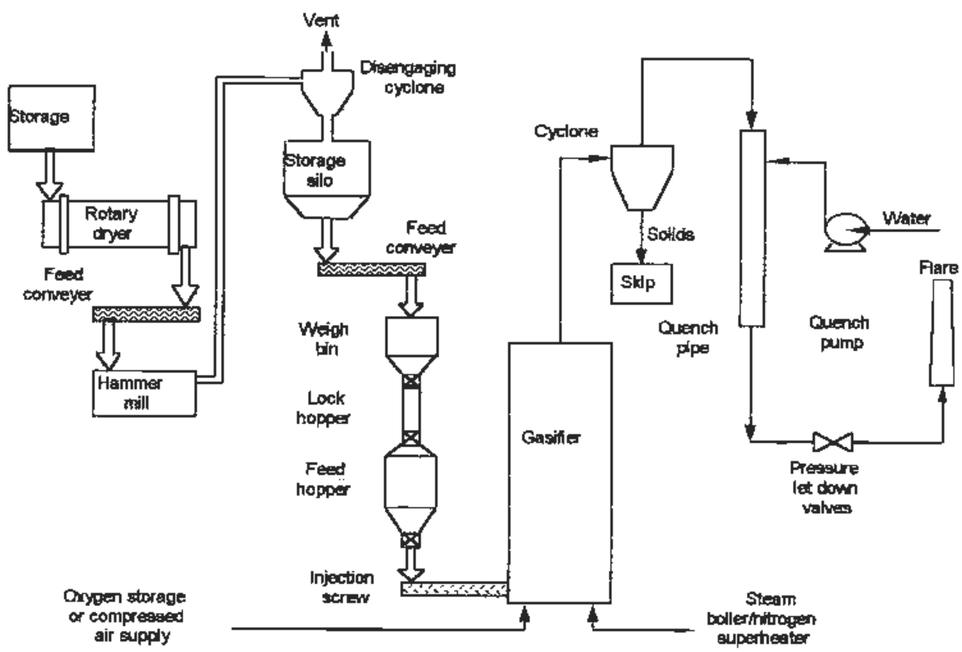

Fig. 1 - Flowsheet of Existing Process

A flowsheet of the IGT process development unit (PDU) is shown in Figure 1 and typical PDU process data is presented in Table 1.

Feed is dried using an off-line rotary drier which serves a number of PDU's. Wood feed is chipped using an on-line hammer mill and screened before being pneumatically transported to a large day-bin. Straw type feed (bagasse, rice straw) is chopped before screening and pneumatic transport to the day hopper. Vibrators are used to prevent feed bridging in the day hopper.

Figure 2 shows the layout of the PDU.

FEED SYSTEM:

Feed from a day hopper is introduced using a chain link conveyor into a small hopper mounted on a load cell and positioned immediately above a lock hopper. Feed from the weighing hopper passes into the lock hopper which is then pressurized to the gasifier operating pressure using nitrogen. In a commercial gasification system, combustion products following product gas utilization would probably be used for lock hopper pressurization. When pressurized, the bottom slide valve in the lock hopper opens and the feed enters a live bottomed, pressurized buffer hopper before transport into the gasifier using a full length screw auger which rotates at a faster speed than the screws in the base of the live bottomed buffer hopper. The base of the live-bottom buffer hopper contains three metering screw feeders. During the wood chips tests the screws rotated in the same direction. However blockages occurred in the buffer hopper during the bagasse tests. The direction of rotation of the center screw at the base of the buffer hopper was reversed, therefore.

In a commercial gasifier, the screw feeder moving the feed into the gasifier vessel would probably be water cooled to prevent pre-pyrolysis of the feed before entering the gasifier. Char which sticks to the end of the screw feeder transporting wood into the PDU gasifier vessel is removed by moving the screw in and out.

During the initial stages of the project, redesign of the lock hopper slide valves was necessary. During the slide valve opening and closing operation, the slide valves were damaging the elastomer seals and the wood chip feed. The damage to the seals resulted in a seal operational life of only 16 hours (two runs). The problem was solved by mounting the valves on jacks and

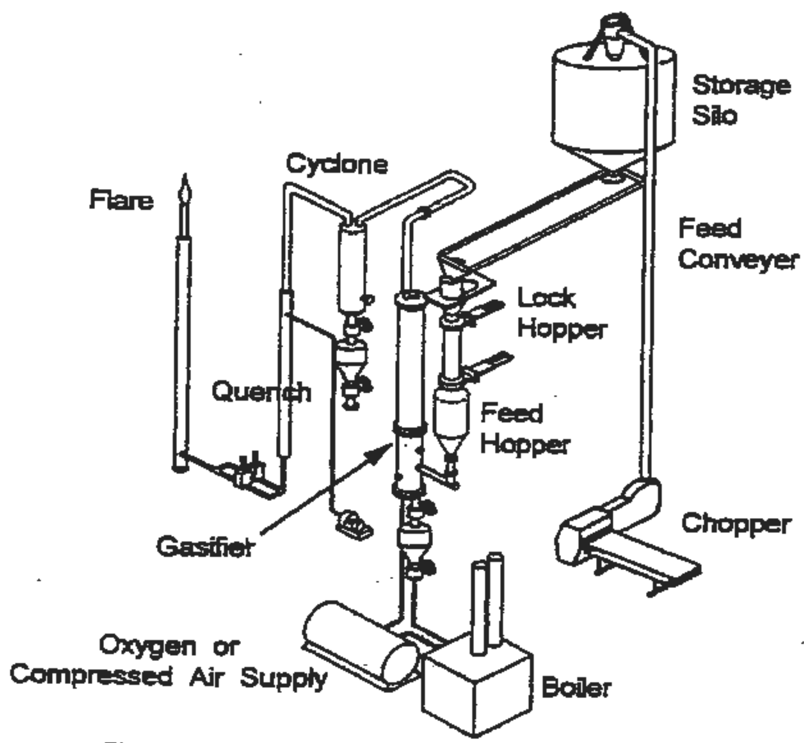

Figure 2 - Layout of Renugas process development unit (PDU)

moving the valves in a horizontal plane slightly lower than the position of the seals during opening and closing operations. When the slide valve is in the closed position, the jacks push the valve upwards to effect a seal. This method of slide valve operation is claimed to work well. The lock hopper and the feed hopper are capable of continuously feeding sized biomass up to 455 kg/h [Kaltschmitt, 1996].

The initial feeding system (Sund) used at the demonstration plant in Hawaii (see Section 8) used two plug ended screw augers fitted in series in place of the lock hopper system employed at the PDU. However, excessive wear shut down the tests in a month. A new live bottom feeder is now in place and being tested (09/25/99).

GASIFIER:

The PDU gasifier vessel has a diameter of 30 cm and a height of 6.7 m. The gasifier diameter increases in the freeboard region to slow down the local velocity and help crack tars. The length to diameter ratio of the bed area is approximately 5 to 6. The bed is composed of aluminum oxide beads (40-70 mesh). The high density of the bed material results in a very low carry over of bed material into the gas stream. In addition, the bed material aids break up of biomass particles in the bed and ensures good heat transfer.

Table 1 - Existing Process Data - Wood Chip Feed ,[Kaltschmitt, 1996]

PROCESS TYPE	FLUIDIZED BED GASIFICATION	
Main feedstock	Woody biomass	
Main product	MHV gas	
Main product yield	2.47	kg/kg daf feed
Main product use	Fuel gas, syngas	
Feedstock throughput - Max	455	kg/h
- Min	136	kg/h
Primary reactor operating pressure	up to 33 bar	
Primary reactor operating temperature	816°C	
Oxygen input rate	0.27	kg/kg daf feed
Steam input rate	0.64	kg/kg daf feed
Liquid	0.03	kg/kg
Solid	0.03	kg/kg

The gasifier is designed to operate adiabaticly at temperatures and pressures up to 982 °C and 32.7 bar with an estimated throughput capacity of 455 kg/h of biomass . The highest pressure tested was 23.8 bar [Niessen, 1996]. The gasifier temperature is controlled by the steam/oxygen ratio. The gasifier was built for steam/oxygen operation although it has been operated using nitrogen diluted steam and oxygen (to simulate air/steam operation as no compressor is installed). The gasifier is fitted with a feed tube to re-inject entrained char if required [Kaltschmitt, 1996].

The product gas is isokineticly sampled as it leaves the gasifier. Following condensation of tars and removal of particulates in the sample stream, the gas is analyzed using a gas chromatograph.

Following the gasifier, the raw gas passes through a pressurized cyclone to remove any solids from the gas [Kaltschmitt, 1996]. Particulates collected by the cyclone are collected in a sealed skip. Following the cyclone, the gas is partially quenched to cool the gases without liquid condensation to enable the product gases to be piped to a flare [Kaltschmitt, 1996] . There is no wastewater emission from the PDU. The final product gas dust content bas not been measured.

PLANNED MODIFICATION, DEVELOPMENTS, EXTENSIONS

Further planned work will investigate hot gas filtration of the product gas (see Section 8).

Feedstocks And Characterization

This process is designed to gasify forest and wood wastes (whole tree chips including some bark and leaves) . As received characteristics are not reported. Both hard and soft woods, dRDF pellets (10 mm diameter, 20 mm length), rice straw, bagasse, paper mill sludge and bark waste have been gasified . Only one test was conducted using RDF.

Prior to use, wood feed is dried in a rotary dryer, passed through a hammer mill and screened to between 1 and 38 mm. Bagasse, however was chopped before use and passed through a 6.35 mm (0.25") screen . The length of the chopped bagasse was approximately 2-5 mm.

The mean feed moisture content of the wood chips tested was 10% (range 5-15%) [Niessen, 1996]. Wood chip feeds containing up to 27% moisture are reported to have been gasified [IGT, 1991]. The mean ash content of the forest and wood wastes was 0.7% (range 0.5-5%) [Niessen, 1996]. The maximum acceptable ash content is not reported.

PRODUCTS

Gas Characteristics

Typical dry gas composition and cbaracteristics are presented in Table 2 . The proportion of tars and particulates in the product gas are not reported.

Liquid Products Characteristics

Some tars and oils are produced which are flared with tbe product gas. The PDU system produces approximately 0.03 kg/kg dry feed of tars and oils This equates to approximately 13.7 kg/h at the system maximum feed throughput. An iso-kinetic sampling system at the gasifier exit is used to measure the liquids production. The estimated higher heating value of the tars/oils is 46.4 MJ/kg .

Solid Products Characteristics

There are no solid products from this process. Some solids are produced by the IGT gasifier which are considered in this profile to be wastes. The solids produced are, therefore, reported in Section 6.3.

PERFORMANCE

The reported overall thermal efficiency (ratio of the cold gas higher heating value to tbe biomass feed higher heating value) is 75% . The turn down ratio is 4:1 (undefined) . In all tests, the product gas tar content was between 2 and 3%. The process was not, however, optimized for high efficiency during the tests [IGT, 1991]. Representative mass and energy balance are shown in Table 3. Process yields and minimum and maximum throughputs are shown in Table 1.

Table 2 - Summary of Typical Gas Characteristics - Wood Chip Feed .

Gas	% volume	
Hydrogen	25.3	
Carbon monoxide	16.0	
Carbon dioxide	39.4	
Methane	17.8	
C_2+	1.5	
O_2, N_2, H_2O	o	
Gas output rate (dry)	335	Nm^3/h
Gas exit temperature from system	816	°C
Heating value	12.97	MJ/Nm^3
Tars content	0.02-0.03	kg/kg feed

System tests using bagasse were reported to be generally successful with a good thermal efficiency. Two tests were performed following successful testing and operation of the feed preparation and handling system. A carbon conversion efficiency of greater than 95% was attained .

A detailed mass and energy balance with 96.4% closures is given based on a 1 hour of running. A total of 5697 MJ was developed.

EMISSIONS

Solid Emissions

The raw gas exiting from the gasifier contains approximately 0.03 kg/kg daf feed of solids (see Table 1) . The solids flowrate is measured using an iso-kinetic sampling probe at the gasifier exit. The solids are sized between 0.01 and 0.06 mm and have an average higher heating value of 27.85 MJ/kg . Most of the solids are removed by the gas cleaning cyclones downstream of the gasifier (see Figure 1) [IGT, 1991].

Pollution Control Technologies

Solids collected by the solids receiver vessel are discharged through a small lock-hopper enabling gasification system operation over extended periods. The efficiency of the solids removal filter and the method of disposal of solids from the gasification system are not reported.

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3.9 EPI, (FORMERLY JWP ENERGY PRODUCTS, PREVIOUSLY ENERGY PRODUCTS OF IDAHO)

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Process: Fluidized bed atmospberic pressure gasifier

PROCESS SUMMARY

The aim of this process is the gasification of biomass in a fluidized bed gasifier for the production of a low heating value gas with a higher heating value of approximately 4-6 MJ/Nm^3 . The hot gas can be used with minimal cleaning to fuel dedicated steam boilers. Three gasification systems each of similar configuration have been built to date (Sacramento, Bloomfield and North Powder). Each of these systems is no longer operational.

DESCRIPTION

Background

EPI is a manufacturer of fluidized bed combustion and gasification systems. Updraft gasifiers have previously been produced. These are no longer produced due to gasifier operational difficulties. There are currently no pilot scale gasifiers at EPI Energy Products although there has previously been a 1.3 MW_{th} (fuel input) gasifier.

In 1981, EPI received a contract to design and construct a (14.2 MW_{th} fuel input, 2.1 m diameter) fluidized bed gasification system to retrofit to an existing central heating boiler for the

State of California . The gasifier was to provide sufficient gas to enable the boiler to produce 20 000 kg/h of steam boiler at 19 bar . The gasifier was started up in December 1982 . This plant was to be fueled with road sweepings. The equipment required to process the city cleanup residue was not delivered on time. This resulted in a low gasifier availability in the first year of operation . It was also found that the fuel quality of the city cleanup waste was poor and insufficient to produce a gas with a high enough heating value to enable sufficient steam to be raised from the steam boiler . This fuel was, therefore, deemed unacceptable and it was necessary to continue operating the plant using wood chips . Due to the high cost of woodchips compared with fossil fuel costs, the plant was subsequently closed.

A second (25 MW_{th} fuel input, 3 m diameter) gasifier was installed at Alternate Gas Inc., Bloomfield, Missouri in Spring 1985. This plant was used to produce low heating value gas to fire an existing rotary kiln and fuel dryer. This plant was closed due to reductions in fossil fuel prices.

A third gasification plant (26.3 MW_{th} fuel input, 3 m diameter), used to produce low heating value gas to fire a boiler (used to produce electricity using a steam turbine), was installed at Catalyst Energy/Idaho Timber Corporation's Crisstad Power Plant at North Powder, Oregon in December 1985. EPI Energy products supplied the fuel receiving, storage, drying and feed conveying systems and the steam generation system. This plant was closed as poor initial availability led to the local power company terminating the contract to purchase electricity from North Powder. This plant is currently being relocated to a site in New York by a third party company.

PROCESS DESCRIPTION

Existing Process

Each of the gasification systems installed by EPI Energy Products has been similar in configuration. The following describes the gasification system installed at North Powder. This was the third and latest gasifier installed by EPI Energy Products.

A flowsheet of the EPI Energy Products 26.3 MW_{th} fluidized bed gasification system gasification system which was installed in North Powder is shown in Figure 1. Design process data is shown in Table 1.

The North Powder system incorporates a fuel receiving and storage facility to unload wood residue from trucks into a reclaimer storage bin. The wet fuel is dried in a rotary drum dryer using the boiler/economizer flue gases prior to metering the fuel into the gasifier. Air is introduced to the bed through nozzles supplied by a series of air manifolds [MURPHY, 1992]. The nozzles are designed to maintain uniform air flow across the entire bed region while the manifolds create a flow path for downward removal of large sized bed contaminants [MURPHY, 1992]. This design enables the bed material to be continually removed, screened of all large material and recycled back to the bed while maintaining continuous reactor operation [MURPHY, 1992].

The fuel is fed to the gasifier using a single screw feeder which deposits the feed material below the fluid bed surface. This reduces the fraction of carbon carry over out of the gasifier [MURPHY, 1992]. A rotary valve as shown in Figure 1 prevents gases escaping into the feed hopper. Air is injected into the feed screw to maintain a positive pressure in the feed system. Feed pre-pyrolysis in the screw probably does occur but the extent to which it occurs is not known.

The screw is not water cooled. Other types of feeder would be used as necessary for other fuel types. The reactor operates at a bed temperature of 650°C [MURPHY, 1992] and at an equivalence ratio of approximately 35% depending on the feed moisture content.

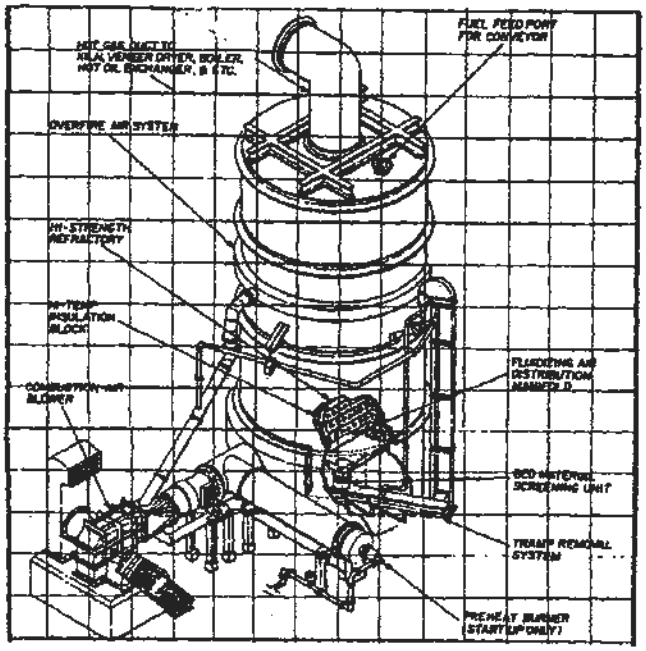

Figure 1 - Flowsheet of EPI Gasification Process Installed at North Powder [Murphy, 1992]

The low beating value product gas was directly fired in a boiler to generate steam for the production of power using a (reconditioned) steam turbine (5.6 MW_e).

No gas cleaning operations are carried out between the gasifier outlet and the boiler. This decision was made to maximize the thermal efficiency of the system [MURPHY, 1992]. The effect of operation without any gas cleaning operations between the boiler and gasifier was to increase the number of problems experienced with boiler operation. Hot refractory surfaces (1100°C) in the boiler furnace led to ash slagging problems. This was further aggravated by initial high fuel ash concentrations. The boiler was reported to quickly exhibit signs of fouling following start up although the time scale is not reported [MURPHY, 1992].

Following the boiler, the flue gases in the North Powder plant are cleaned in a 152 mm diameter multiple cyclone before entering an economizer. The hot gases leaving the economizer are passed through a single pass rotary drum dryer. Under normal inlet feed moisture levels of 37%, this dryer could dry the fuel to 25% moisture content.

Problems during commissioning of the first gasification system which was installed at Sacramento included gas leaks and screw feeder overloads due to ash and sand agglomerating during start-up and shut-down periods .

Table 1 - Process Data (North Powder Plant) [MURPHY, 1992]

PROCESS TYPE	**FLUIDIZED BED GASIFICATION**	
Main feedstock	Wood chips, sawdust	
Main product	Low heating value gas	
Main product yield	3.0	kg/kg feed *
Main product use	Steam raising using conventional steam boiler	
Feedstock throughput (design)	4134.1	kg/h
Reactor type	Fluidized bed	
Primary reactor operating pressure	1	Bar
Primary reactor operating temperature	650	°C
Reactant	Air	
Reactant input rate	2.00	kg/kg feed
Solid waste flowrate	0.04	kg/kg feed

PLANNED MODIFICATION, DEVELOPMENTS, EXTENSIONS

It is reported that in future projects, EPI would include a hot cyclone between the gasifier and boiler [MURPHY, 1992]. Although the overall fuel efficiency is increased and most of the char is consumed in the boiler furnace by the exclusion of the cyclone, the increased ash input to the boiler creates boiler control and reliability problems [MURPHY, 1992]. Boiler fouling would be significantly reduced by removing 60-70% of the particulates in the raw product gas using a cyclone [MURPHY, 1992].

Removal of the particulates in the gas would reduce the gasifier efficiency by a reported 7-10% although this will vary with fuel size and gasifier operation [MURPHY, 1992]. Options for the use of char removed by the cyclone include char recycling back to the gasifier and the manufacture of charcoal briquettes for sale [MURPHY, 1992]. This second option would eliminate the need for char/ash disposal. The char/ash mixture removed by the cyclones installed between the gasifier and boiler/furnace in the first two plants installed by EPI Energy Products was not recycled back to the gasifier.

The extent of gas cleanup for future plants would vary according to the gas utilization process. To date, the only proven application applied to the EPI gasification technology has been boiler and furnace firing. Engine fueling has not been tested although such an application would be considered. For boiler/furnace fueling, only minimal cleaning is required (usually a cyclone) while for engine use, further gas cleanup would be required. Cleanup technologies which would be considered are: wet scrubbing (although this would lead to a waste water disposal problem and the removal of gas sensible energy), electrostatic precipitators and hot gas filtration (which has not been tested by EPI Energy Products). EPI Energy Products recognize that further development work (up to 24 weeks) would be required to provide performance guarantees for a gasifier/engine system following construction of a pilot scale gasification plant.

FEEDSTOCKS AND CHARACTERISATION

Feedstocks tested by EPI Energy Products include:

- wood chips
- Sawdust
- Demolition wood waste
- Urban waste wood
- Rice hulls
- Various agricultural wastes
- Dried raw sewage sludge

The feed design specification for the Sacramento installation was for wood chips with a moisture content of less than 30% (wet basis), an ash content of less than 5%, a particle size of 25 mm and an higher heating value of approximately 17.55 MJ/kg .

PRODUCTS

Gas characteristics

The product gas from the EPI Energy Products gasifier is a low heating value gas (4-6 MJ/Nm^3) with a tar content of approximately 15% of the input wood energy. A summary of the reported gas characteristics including the gas heating value and temperature is shown in Table 2.

Liquid Products Characteristics

The gasifiers constructed to date produced no liquid products. Any tars produced are combusted in the boiler.

Solid Products Characteristics

The gasifiers constructed to date produced no solid products.

PERFORMANCE

Performance testing has shown the overall efficiency of the plant shown in Figure 1 to steam to be 74.1% with a feed moisture content of 46% [MURPHY, 1992].

Design mass and energy balances for the Sacramento gasifier are presented in Table 3 while an energy balance (Sacramento) calculated from measured data is shown in Table 4. The design fuel throughput (Sacramento) was 4134 kg/h while the measured feed throughput was 3078 kg/h . The maximum and minimum throughputs are not reported.

Table 2 - Summary of Gas Characteristics (North Powder) [MURPHY, 1992]

GAS	% VOLUME
Hydrogen	5.80
Carbon monoxide	17.50
Carbon dioxide	15.80
Methane	4.65
C_2+	2.58
Oxygen	0.80
Nitrogen	51.90
Cl_2, S, H_2O	0
Total	99.03

Gas exit temperature from gasifier, 621.1°C; High Heating value 5.60MJ/Nm^3

Table 3 - Design Mass and Energy Balances over Gasifier

Inputs	Kg/hr	MJ/hr
Fuel feed	4134.1	53357.3
Air	8309.5	0
Total	12443.6	53357.3
Outputs		
Hot gas	12274.0	49240.5
Char	61.2	2004.2
Ash	108.4	0
Losses *	-	533.6
Total	12443.6	51778.3
Closure, %	100.0	97.0
Hot gas efficiency, %		92.3
Cold gas efficiency, %		64.6

*** Assuming: gas temperature = 621.1°C, gas specific heat =1.2KJ/kgK [Reyes, 1988] ; Assuming heat losses from gasifier equal 1% of the feed energy input**

As the char removed hy the cyclone is not reinjected into the fluidized bed, there is a loss of approximately 6% (measured data) of the feed energy input (Sacramento gasifier) . The design char energy loss rate is 3.7% of the feed input energy (see Section 2.2.2) . Higher losses due to char were encountered when using sawdust as a fuel as a higher quantity of material was entrained from the bed before it could be completely gasified .

A turn down ratio of 3:1 is claimed.

The Sacramento gasifier was operated at an availability of less than 100% during the first year of operation (1983) due to fuel supply problems (see Section 2). During operation, the system performed well and was capable of maintaining and following the load over a wide range of output.

Gas Emissions

The EPI gasifier produces no gaseous emissions. The whole gasification system as shown in Figure 1 will, however emit cooled combustion products. The use of a low NO_X burner and selective non catalytic reduction if necessary can produce low flue gas NO_X levels (<0.08% NO_X can be achieved). Efficient furnace design to ensure a long residence time and good gas mixing will ensure low hydrocarbon and carbon monoxide levels. However, if the combustion temperature is too high, then there is a danger of atmospheric NO_X formation and ash slagging. It is reported that a wet scrubber was considered for use at the North Powder gasification plant (Figure 1) to meet Oregon air quality requirements (0.1 g/scf) [MURPHY, 1992].

Table 4 - Energy Balance Over Gasifier (Measured)

Inputs	MJ/h
Air	0
Feed	47078.1
Total	47078.1
Outputs	MJ/h
Hot gas	43808.0
Char	2795.4
Heat losses*	474.7
Total	47078.1
Closure, %	100.0
Hot gas efficiency, %	93.0

*** 1% of feed input Gas temperature 680°C**

Liquid Emissions

The product gas tar content is approximately 15% of the input wood energy.

Pollution Control Technologies

Tars and condensables produced by the gasifier in each of the three installations to date were fired with the product gas in the boiler.

Solid Emissions

In the case of the North Powder plant, this consists of ash removed from the cyclone, the boiler and from the bottom of the gasifier. Most ash exits the gasifier as fly ash.

The solid waste products from the Bloomfield and Sacramento installations consisted of ash and carbon. The ash and char are removed from the product gas using a cyclone downstream of the gasifier. The design ash and char production rate for the Sacramento gasifier was 169.6 kg/h (61.2 kg/h char and 108.4 kg/h ash) .

Due to the almost complete burnout of the ash at North Powder, the ash was landfilled. Disposal of the ash from the Sacramento and Bloomfield sites was more difficult due to the presence of char.

Disposal of the ash following the gasification of sewage sludge would be more difficult as the ash could contain heavy metals. In the case of sewage sludge, therefore, specialized disposal would be required.

PROCESS COSTS

The estimated capital cost of a 166 tonne/day fluidized hed gasifier in 1981 was US$1.58 million [Anon, 1981]. This includes the gasifier, fuel metering, after-burner, refractory duct, emission controls, fuel handling and storage, control equipment and installation [Anon, 1981]. This is equivalent to approximately US$9 518 per tonne/day feed.

Operating Costs

Estimated annual operating costs excluding feed costs in 1981 (350 days/year) were US$685 200 [Anon, 1981]. This includes depreciation (10% of capital cost), maintenance (3% of capital cost), taxes and insurance (2% of capital cost), interest (12% of capital cost), labor (US$15/hour) and utilities (300 hp, US$0.60/kW) [Anon, 1981].

Estimated fuel costs of wood chips in 1981 were US$20 /ton. The total requirement for a 166 tonne/day plant is for 58082 wet tons per year (40% moisture content, basis not reported) at a cost of US$1.1433 million [Anon, 1981].

MARKETS FOR PRODUCT

The market for the EPI Energy Products gasification system is seen mainly as retrofit to existing gas boilers. The competition for new sites for steam raising from combustion systems is too great. The future advantage for gasification is seen as the IGCC system where a high efficiency to electricity can be realized. Currently, the largest gasifier which would be built would be 171 MW_{th} feed input (650 MBtu/h).

The patent for the EPI Energy Products gasifier is held by EPI Energy Products. Manufacture takes place in Couer d'Alene. Some plant items such as fans, pumps and valves would probably be sourced locally for a gasification system to be built outside the USA. Licensed manufacture in other countries is also a possibility.

CURRENT STATUS

In a telephone conversation with M. L. Murphy I learned that they are not currently making a gasifier, but are negotiating with several prospective buyers. The company name has changed back from EPI to EPI, the original name. The North Powder gasifier has been relocated to Iowa, due to removal of tax subsidiers, and is now burning residues there.

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3.10 Lurgi Energie- und Umwelttechnik GmbH

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PROCESS: Circulating Fluid Bed Gasifier for power generation, cement or lime kilns

SUMMARY

The main objective of this project is the gasification of wood, RDF or coal for the production of a low or medium heating value fuel gas in a circulating fluidized bed gasifier. The throughput of the installed commercial system is approximately 6500 kg/h daf (8030 kg/h at 15% moisture content and 5% ash content) and there is one pilot unit operating at atmospheric pressure with air or oxygen. A modified gasification system operating on oxygen and steam can produce synthesis gas for subsequent conversion to methanol or other chemicals [Herbert, 1989; REIMERT, 1984].

DESCRIPTION

Pilot Plants

Lurgi has a gasification pilot plant at the Frankfurt/Main R & D center. The output of this plant is $3MW_{th}$ (approximately 1000kg/h) for oxygen blown operation and approximately 1.7 MW_{th} for air blown operation.

Commercial plant

A Lurgi circulating fluidized bed bark gasification system (atmospheric operation) was installed in 1986 at Zellstoffwerke Pöls AG (ZPA), an Austrian pulp producer, for the production of a low heating value gas from bark to fuel a lime kiln originally fueled by oil. This plant is currently operational as of April 1992. The system is not yet running at full capacity since a boiler to be fueled with low heating value gas is not yet installed. The current feedrate is between 3500 and 4500 kg/h.

A process flow diagram of the commercial Lurgi CFB bark gasification plant at Pöls is shown in Figure 1 while process data (from bark gasification) is presented in Table 1. The following description describes the gasification plant at Pöls.

Prior to gasification, wet bark is dried in a rotary drier fueled by up to 20% of the product gas from tbe gasifier. Waste heat from pulp production is not used for feed drying purposes to prevent SO_2/SO_3 emissions from the drier which may lead to corrosion of the drier. Off-gases from the dryer are water scrubbed. Waste water from the scrubber is added to the pulp process and does not, therefore, result in a waste water disposal problem.

Dry bark is stored in a metering bin prior to feeding into the gasifier through screw feeders (Figure 1). Ash is cooled following removal from the gasifier as shown in Figure 1. The cooled ash is subsequently landfilled.

Some sensihle heat is recovered from the hot gas for inlet air pre-heating. Following cooling, the gas passes through a cyclone before the utilization process. The solids removed from the gas in this cyclone are returned to the gasifier as shown in Figure 1.

Heavy feed moisture fluctuations and excessive metal and large wood pieces in the dry hark have previously made gasification difficult. Metal detection and removal methods, stone removal methods and control and operating procedures at the Pöls plant have since been improved.

The low heating value gas is used to fuel a lime kiln fitted with a multifuel burner (heavy oil, LHV gas and off gases from the pulp production process) at the Pöls plant. The total LHV gas demand by the lime kiln is 8000Nm^3/h.

FUTURE PLANS AND PROSPECTS

Biomass gasification at elevated pressure using the High Temperature Winkler (HTW) process is at the development stage. Laboratory scale tests using biomass have been conducted. The HTW pilot plant has yet to be tested using biomass.

Lurgi is currently investigating hydrogen production from biomass and gasification of wastes. Internal combustion engine and gas turbine operation fueled using low heating value gas is also under investigation.

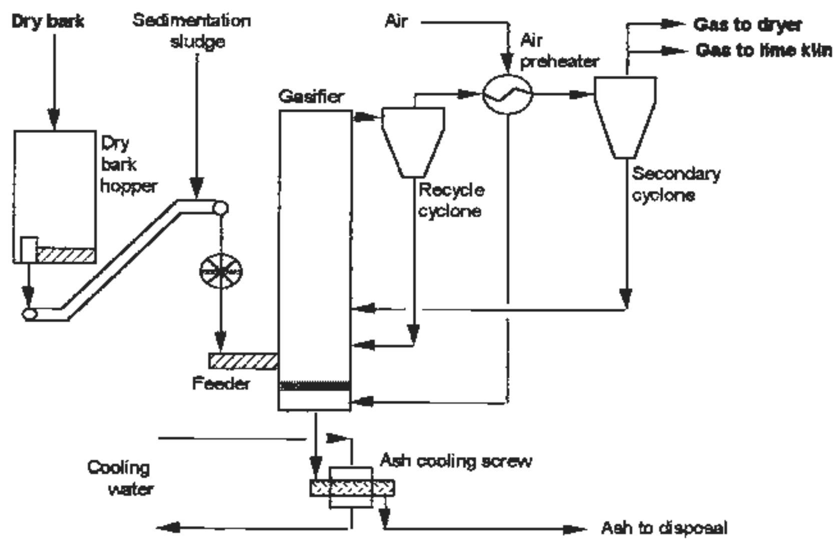

Figure 1 - Lurgi CFB Gasification System at Pöls Pulp Mill [Herbert, 1989]

FEEDSTOCKS AND CHARACTERISATION

Rice husks, straw, bark, wood waste, wood, whole tree chips, RDF, coal and petroleum coke are suitable feedstocks for the Lurgi CFB gasification system [Herbert, 1989; Anon, 1981]. The gasification plant at Pöls is designed for the gasification of bark [Herbert, 1989]. The bark is dried before use from between 54 and 63 wt% to approximately 10 wt%. For other applications, a higher moisture content feed may be tolerable. The bark is shredded to a maximum size of 30mm at Pöls [Herbert, 1989]. SAWDUST is a highly suitable feedstock.

PRODUCTS

Gas Characteristics

The main product of the atmospheric gasification process is a low heating value gas with a heating value of 5.8 MJ/Nm^3 from bark feed (this value includes the heating value of any tars and particulates and the sensible heat of the gas). Particulates separated from the gas are returned to the gasifier. This results in good carbon conversion efficiency [Herbert, 1989]. The product gas has a very low tar content of approximately 1 g/Nm^3 due to the high gasification temperature (800°C) and is practically sulfur free [Herbert, 1989]. The gas is sufficiently clean for use in the calcination process. The reported clean gas compositions from the gasification of bark are shown in Table 2.

Liquid Products Characteristics

The Lurgi gasification system produces very few tars ($<1 g/Nm^3$) due to the high gasification temperature [Herbert, 1989].

Table 1 - Existing Process Data (Commercial Plant) [Herbert, 1989]

Process	Circulating Fluid Bed Gasification
Feedstock	Bark, RDF*, wood, lignite coal petroleum coke, waste wood,
Main product	Low heating value gas
Main product yield	1.2-1.3 kg/kg daf feed
Main product use	Lime kiln firing
Feedstock throughput*	3500-4500 kg/h
Reactor type	Circulating fluid bed
Primary reactor operating pressure	1 bar
Primary reactor operating temperature	800°C
Reactant	Air
Reactant input rate	1.23-1.26 kg/kg feed
Gaseous waste flowrate	0
Liquid waste flowrate (from dryer scrubber)	low
Solid waste flowrate, ash ƒ	0.01-0.04 kg/kg feed

***Tested at Frankfurt R&D center † Feed moisture content: 15%; feed ash content: 5% ƒ Ash carbon content: 1.5-3.3 wt%**

PERFORMANCE

The reported product gas yield from the commercial scale atmospheric gasification plant at Pöls is 3.1 kg/kg daf feed.

The product gas from the gasification of RDF was claimed to contain no detectable dioxins [Herbert, 1989]. The suitability of gas produced from RDF for cement kiln firing was under evaluation in 1989 [Herbert, 1989]. Gas composition data from the gasification of RDF is shown in Table 3.

The design availability of the Pöls bark gasification plant is 95%. Currently, the plant is operating at 60% capacity as a boiler intended to utilize a proportion of the product gas is not yet installed [Herbert, 1989],[REIMERT, 1984].

EMISSIONS

Gas

All gaseous products from the gasification plant at Pöls are combusted in a lime kiln. Following combustion of the gas, the lime kiln will emit gaseous combustion products.

Table 2 - Summary of Gas Characteristics from Pöls Bark Gasification Plant [Herbert, 1989],[REIMERT, 1984]

Gas	% volume dry
Hydrogen	20.2
Carbon monoxide	19.6
Carbon dioxide	13.5
Methane	included with C_2+
C_2+	3.8
Nitrogen	42.9
Sulfur	very low
Design gas output rate (dry)	9700-12500 Nm^3/h
Gas exit temperature from system	600°C
Heating value	5.8 MJ/Nm^3
Particulate content (measured during pilot plant tests)	50 g/Nm^3

At the Pöls gasification plant, the gasification system includes a dryer which will produce gaseous emissions. The gaseous emissions produced are within the official emission limits (see Table 4).

Liquid

The dryer at Pöls incorporates a water scrubber. Waste water from the scrubber is treated with waste water from the pulp mill and is reported not to be a difficulty.

Solid Emissions

The ash production rate from the Pöls bark CFB gasification plant is reported to be between 0.03 and 0.18 t/h (0.009-0.050kg/kg daf feed) [Herbert, 1989]. The carbon content of the ash is between 1.5 and 3.3wt% [Herbert, 1989].

Table 3 - Summary of Clean Gas Characteristics from the Pilot Scale CFB Gasification of RDF [Woelke, 1992]

GAS	% VOLUME
Hydrogen	8.27
Carbon monoxide	9.76
Carbon dioxide	9.30
Methane	1.55
C_2+	0.64
Oxygen	0
Nitrogen	43.06
H_2S	0.07
H_2O	27.35
Heating value (lower)	3.2 MJ/Nm^3
Heavy metals content (define)	<1.1 mg/Nm^3
HCl	18 mg/Nm^3
HF	1.8 mg/Nm3
Dioxins	<0.1 mg/Nm3
Particulate content	18 mg/Nm3

Table 4 Official Emission Limits (Relative to *7% Volume Oxygen)*

CONTAMINANT	CONCENTRATION, mg/m^3
Dust	50
SO_2	100
NO_x	250
CO	250
H_2S	5
Organic carbon	150
NH_3	5
Chloride/Fluoride	6

Pollution Control Technologies

Ash from the Pöls bark gasification system is landfilled. It is reported that gasifier bottom ash from the RDF gasification tests was suitable for disposal in regular municipal refuse disposal tips.

Capital Costs

The capital cost of a Lurgi CFB gasification system will depend on a number of factors including the feedstock and utilization process. Excluding finance and land purchase costs, a plant similar in design and size to the plant at Pöls (total installed cost including bark shredding and handling equipment) would be of the order of Dm21 million (£7.5 million).

For a cogeneration plant of $5MW_e$ and $10MW_{th}$ (see Figure 2), the investment cost was estimated to be Dm9 million (£3.23 million) in 1984 [Riemert, 1984]. Product or Production Costs

For a zero feedstock cost, the production cost of the low heating value gas at Pöls is reported to be 152 MJ/Dm, $4.04 /GJ (compared with heavy oil at 221 MJ/Dm, $2.78 /GJ).

MARKETS FOR PRODUCT

The gas produced is suitable for a number of processes including reduction of certain metal oxides, lime kiln firing, substitution of part of the fuel for cement kilns etc. (see Table 4) [Herbert, 1989].

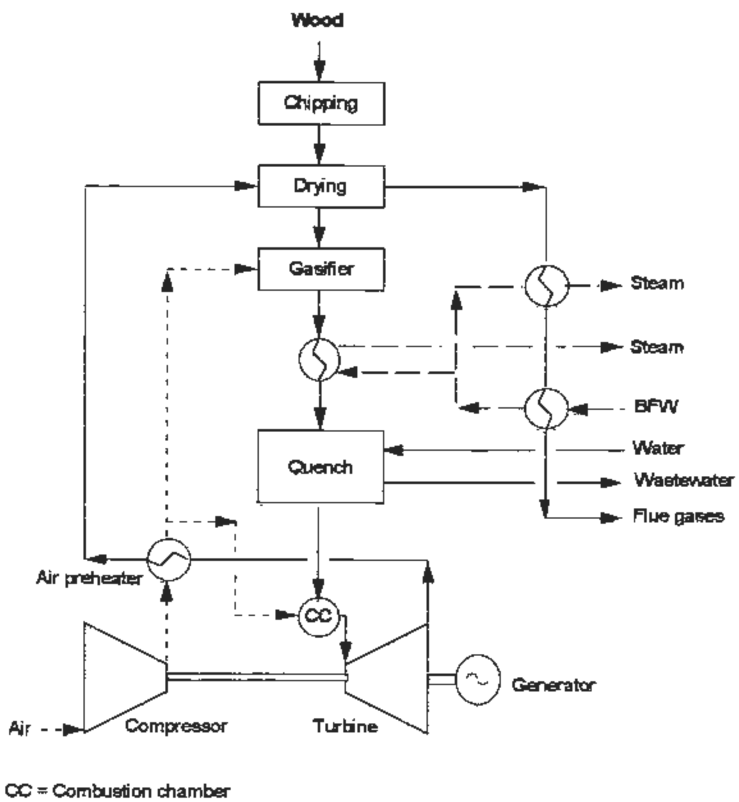

Figure 2 - Lurgi Gas Turbine Heat and Power Cogeneration Scheme [7]

The largest gasifier which would currently be constructed by Lurgi would be of the order of 30 ton/hour of wood (ie a five fold scale up from the current plant at Pöls). The maximum plant size is limited by the feeding system and the logistics of biomass transport to the plant. The minimum plant size is limited by economics and the tipping fee obtained.

Table 5 - Examples of Commercial Applications for Lurgi Gasification System [Anon, ND]

FUEL GAS (AIR BLOWN)

- ☐ Pulp and paper industry
- ☐ Ceramic industry
- ☐ Glass industry

RAW SYNTHESIS GAS (OXYGEN BLOWN)

- ☐ Ammonia
- ☐ Methanol
- ☐ Fuel methanol

FUEL FOR COMBUSTION ENGINES

- ☐ (Gas turbine, IC engine) - Generation of power and process heat for:
- ☐ Sawmills
- ☐ Pulp and paper industry
- ☐ Utilities

CURRENT STATUS AND FUTURE PLANS

The bark CFB gasification plant at Pöls and the pilot scale gasification plant in Frankfurt are currently operational. The license for the pressurized gasification system (termed the High Temperature Winkler gasifier, HTW) is held by Rheimische Braunhole AG, a mining company owned by RWE (the largest German utility).

The following note appeared was sent to the GASIFICATION group at Crest in early 1999. The Lurgi Lentjes Standardkessel AG is to supply two biomass fired power plants for Spain (January 4, 1999) for the supply of two turnkey biomass-fired power plants generating energy from olive pulp in Spain. The two plants were sold for a total contract value of DM 90.1 million and will be the largest power plants in Europe exclusively fired with biomass.

The first Biomass-to-gas plant in the Netherlands (May 19, 1998) was commissioned by N.V> Electriciteits-Produktiermaatschappij Zuid-Nederland, EPZ with the construction of a plant for the production and cleaning of fuel gas from CO_2 neutral fuels (wood) at the Amercentrale location in Geertruidenberg. The process has a special feature in that the gas production unit is coupled with an existing power plant. The concomitant substitution of bituminous coal meets the global demand for CO_2 abatement.

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3.11 PRODUCER RICE MILL ENERGY SYSTEMS, PRMES

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PROCESS: Air controlled updraft gasifier for heat applications

Possibly more biomass has been gasified in PRMES gasifiers than all other gasifiers combined since World War II. It is truly commercial with over 20 current installations and another 8 planned.

A site visit to the new Cargill Grains Greenville MI plant with R. Bailie, Sr. was made by TBR, 12/22/95. At that time the shakedown was essentially completed and the boiler and plant were in full operation.. Minor modifications to the control tower were in progress.

The PRMES technology was developed in the early 1980's by Mr. Don King and Mr. Charles Castain at Producers Rice Mills in Stuttgart Arkansas. The development word was done under the direction of Ron Bailey, Sr., President and CEO of Producers Rice Mills from 1967-1988. Upon Bailey's retirement in 1988, PRMES acquired the patents and began commercialization of the technology.

The installation at Cargill, Greenville MI, consists of two rice hull storage bins, 150 tons each, an automated feed system, two PRMES Model KC 18 gasifiers, each with a capacity of 7.0 tons/hr; a hot combustible gas delivery system coupled to the boiler and a 7.5 MW steam turbine. The gasifiers have zoned delivery of gasification air to the grate, zoned three staged combustion air and removal of the ash through water cooled screws to an ash conveying and storage system. First and second stage combustion air is added to the gas as it enters a specially designed combustion tube to crack and burn tars and hydrocarbons. Final combustion of the gases is accomplished in the boiler furnace. The installation is fully automated based upon feed rate and a number of temperature measurements. The boiler has a mechanical dust collector, an ID fan and stack.

Carbon conversion is incomplete in the gasification of rice hulls, producing an ash byproduct containing 30-35 percent carbon. The ash residue is marketed as an insulating topping for ladles and tundishes in the steel industry.

The complete gasification system was fabricated and pre-assembled by PRIME Inc. in its shops in Tulsa, Oklahoma. The system was loaded on a river barge on the Arkansas River and shipped to the Cargill site. The barge arrived at the Port of Greenville Aug. 29, 1995 and the gasification system was started on October 15, 1995. Various parts are also manufactured by overseas contractors.

PRMES has 13 operating systems in the US, Australia, Malaysia, and Costa Rica, ranging in size from 30-330 tons/day. A 600ton/day system and a 150 ton/day system are under construction in Stuttgart, AK and Jonesboro, AK, USA.

PRMES and Heater Specialists, Inc. have formed PRiMEnergy, Inc. of Tulsa, OK. A full scale PRMES gasification test/demonstration system is in operation at the PRiMEnergy research center in Tulsa. Complete operational and environmental demonstrations have been successfully completed on rice hulls, green bark, MDF fiber, sander dust and other biomass feed stocks. The PRiME test center is available for demonstrating the PRMES gasification technology on all types of biomass feed stocks.

PRIME has been in business since 1983.

DESCRIPTION

The gasifiers use rice hulls from the plant, typically with a moisture content of 8-12%. The gasifier has an agitated bed with 3 air zones under a perforated grate, coupled to a boiler. The feeder uses a metering bin and impact weigh transporter. Two gasifiers using 7 tons of rice hulls/hr each (175 Mbtu/hr) operate simultaneously. The ash is removed with a water cooled screw. The gasifier has been in operation since October, 1995 and is expected to have greater than 20 years of lifetime. [Bailey, 1998]

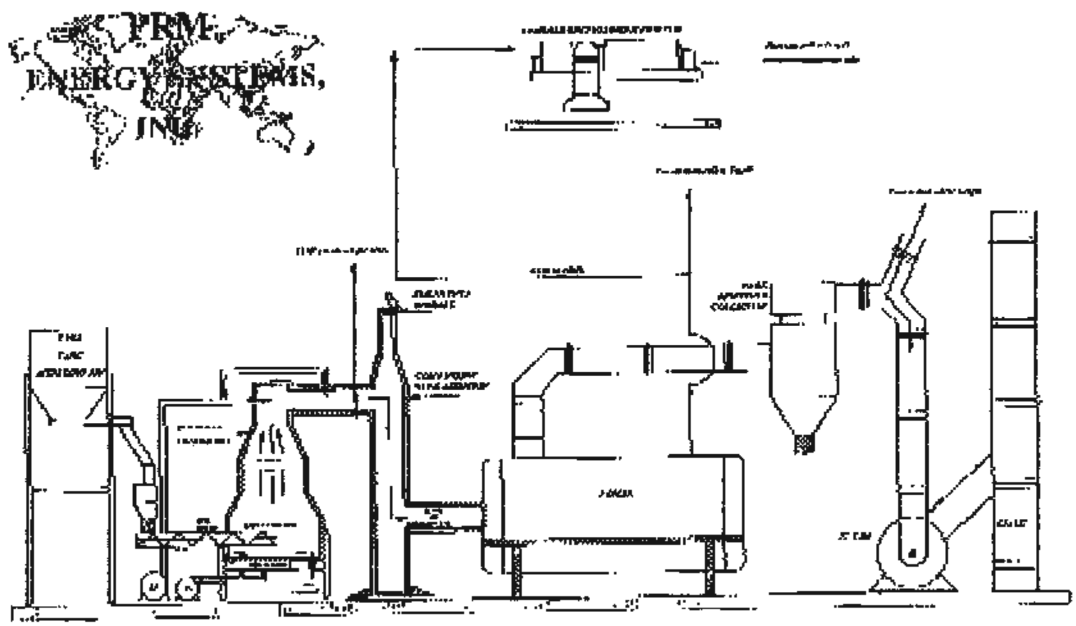

Figure 1 - Flow Diagram of PRMES Rice Hull Gasification Plant

The gas is used for drying and parboiling rice and power generation in a 7.5 MW steam turbine operating at 450 psig, 600°F

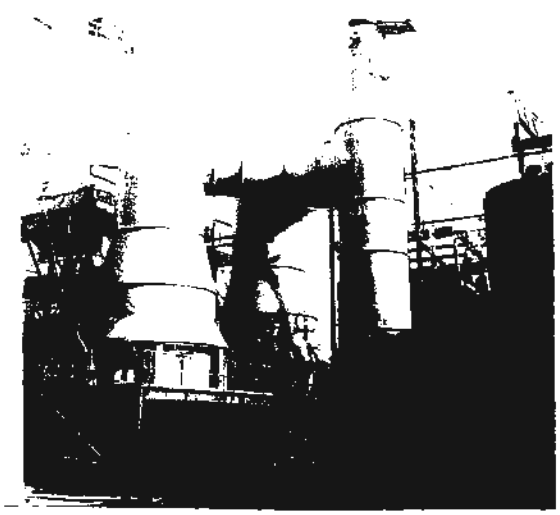

Figure 2- 330 ton/day PRMES installation at Greenville, MI

The average gas composition is: H_2, 12%; CO-8.4%; CH_4 1.0%, all in mole %. The gas temperature at the top of tbe bed is 750 °C, and is increased to 1100°C with excess air passing to the boiler.

Since the gasifier is close coupled there is no gas cleanup on the gasifiers; there is a mechanical dust collector on the boiler exhaust. Maintenance is minimal and done annually.

The gasifier is fully instrumented and automated, PLC based. One low skilled operator is required per shift, trained on the job.

The two gasifiers cost $3.0 M. Close cooperation between the supplier of the boiler, ID fan, as burners and ash handling system and PRMES is mandatory.

PRM Energy Systems has also designed biomass gasification systems for direct drying of MDF fiber, utilizing sander dust, sawdust and bark as feedstock; kiln drying, both steam and hot air; municipal waste water and sewage sludge gasification; VOC destruction utilizing wood wastes to fire rotary chip dryers and gasification/power generation utilizing processed MUNICIPAL SOLID WASTE.

[Bailey, 1998] Bailey, R., Company brochures

3.12 Purox Process (Union Carbide)

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Telephone: 415 345 1338

Fax:

Process: Fixed bed updraft slagging gasifier for disposal of MSW producing medium energy gas.

This description is included for historical purposes as an example of a good process introduced at a time when energy and waste disposal were not the driving force they are today. It was far – too far – ahead of its time.

Since 1975, the U.S. Department of Energy (under various names) has been the nominal government patron of municipal waste gasification. Before this however a number of projects were funded by the U.S. Environmental Protection Agency. Others were funded by private corporations. In 1974 I became interested in methanol as a clean alternative to gasoline that can be made from gas, coal, wood or even municipal waste. About that time a close friend of mine, John E. Anderson, at the Linde division of Union Carbide developed and patented a slagging oxygen gasifier which potentially could make methanol synthesis gas ($CO + H_2$) from MSW [US Patent, 3,729,928 et seq, 1973]. This was called the "Purox Process". (The patents were retained by Union Carbide when Praxair separated from Union Carbide in 1992). This is possibly the longest operating gasifier of biomass to date [Purox, 1979].

The company believed in this process sufficiently to fund the process internally, probably for over $100M. A 200 t/d plant was built and operated for several years in South Charleston, W. Va. The process was developed through the stages shown in Table 1. I visited the Tarrytown 10 t/d pilot plant in 1974. A diagrammatic sketch of the Purox gasification system is shown in Figure 1. The 200 ton/day gasifier is shown in Fig. 2. It is built much like a blast furnace for reducing iron oxides. It consists of a vertical shaft furnace into which waste is introduced through a feeder at the top. Oxygen is injected into the combustion zone at the bottom of the furnace where it reacts with carbon char residue from the pyrolysis zone. The temperature generated in the combustion zone is sufficiently high to melt and fuse all noncombustible materials. The molten material continuously overflows into a water quench tank where it forms a nonleaching, sterile gravel. It consumed 0.2 tons of oxygen per ton of MSW.

Table 1 - History of the Development of the Purox MSW Gasifier

Location	Size - t/d	Years
Tarrytown, NY	10 t/d	1970-1973
South Charleston, W. Va.	200	1974-1978
Tonowanda, NY	10 TPD	1979
Showa Denko, Chichibu, Japan	2 (100)	1981 – 1997

The hot gases formed by the reaction of oxygen and carbon char rise through the descending waste. In the middle portion of the gasifier organic materials are pyrolysed to yield a gaseous mixture typically 38% CO and 23% H_2, dry basis. The high thermal efficiency of the gasifier is indicated by the low exit temperature, 180-300°C, of the gases. A gas cleaning train removes particulates and condensibles and recycles them to the gasifier, leaving a clean (370 Btu/scf) gas which can be used for heat or chemical synthesis applications. A typical gas analysis is shown in Table 1 A number of attempts were made to find municipalities willing to operate very

large MSW plants with energy recovery in the U.S., but the "not in my backyard" climate prevented any plants from being built in the U.S.

Eventually the process was licensed to Showa Denko in Japan and operated for through 1997 there. I have talked to Mr.Tamura in their California office. He was very familiar with the process and worked with it from it's beginning in Japan.

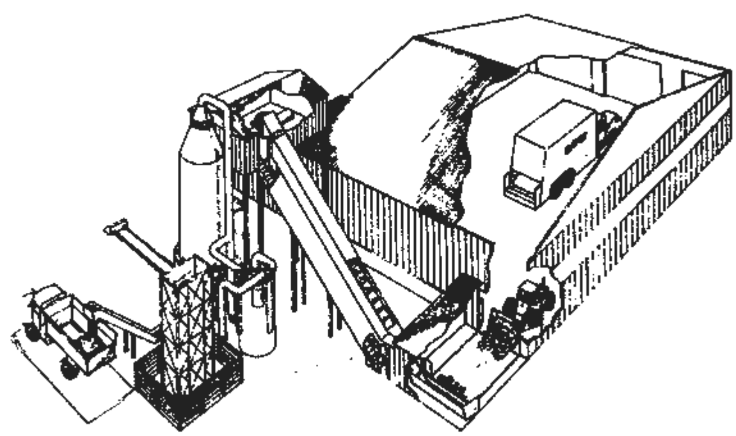

Figure 1 Diagrammatic sketch of the Purox oxygen slagging gasification system

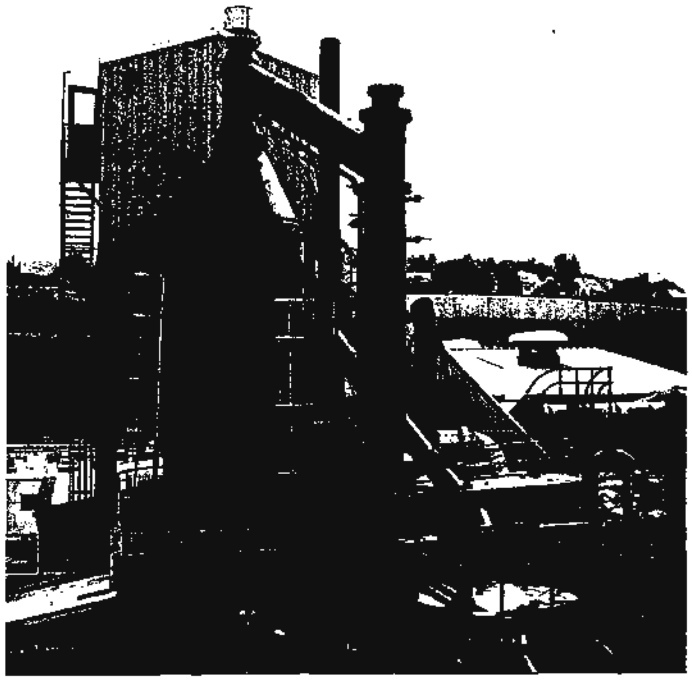

Figure 2 - The 200 ton/day Purox oxygen gasifier in South Charleston, W. Va.

The gasifier was constructed 20 years ago in Chichibu, Japan. Because of government guidelines the gas couldn't be used for power generation, so the gas was flared and disposal of MSW was its only function.

The removal of "Tar" (volatile organics) from the raw gas from updraft gasifiers has always been a major disadvantage of updraft gasification. However, a good deal of research has been done on catalytic tar removal in the last decade. It is possible that a fresh look should be taken at the Purox and Andco Torrax processes with new gas cleanup possibilities in mind.

The gasifier consumed only 75 tons/day of waste, far below the level considered economic in the U.S. In the U.S. plant the waste was inserted as large pellets, but not in Japan. The gasifier consumed 0.2 kg O_2/kg waste. Oxygen was manufactured using the pressure swing process. The gas was cooled with a water spray, then passed to the cyclones, then to an electrostatic precipitator for cleanup. The molten slag was quenched in hot water and disposed as landfill. Initially Japanese waste contained 40% metal, but current recycling has reduced the slag almost to zero. A Mr. Yeasui in Japan is the plant engineer, at 011 81 3 3457 5111.

Table 1 - Typical gas analysis from the Purox MSW slagging oxygen gasifier

Component	Volume Percent
H_2	23.43
CO	39.06
CO_2	24.41
CH_4	5.47
Acetylenes	0.68
Ethylene	2.05
Ethane	0.29
Propylene	0.29
Propane	0.19
Higher hydrocarbons	1.43
H2S	0.05
Methanol	0.10

3.13 Skygas (Unitel)

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Address: Unitel Technologies, Inc., 411 Business Center Drive, Su 111, Mount Prospect, IL 60045.

Telephone: 847 297 2265

Fax: 847 297 1365

Purpose: Electric Arc Fixed Bed Gasifier for Syn-gas, methanol

Skygas is an innovative electric arc process for the gasification of carbonaceous wastes to a medium energy gas. The process has been demonstrated in a 4 ton/hr process development unit (PDU).

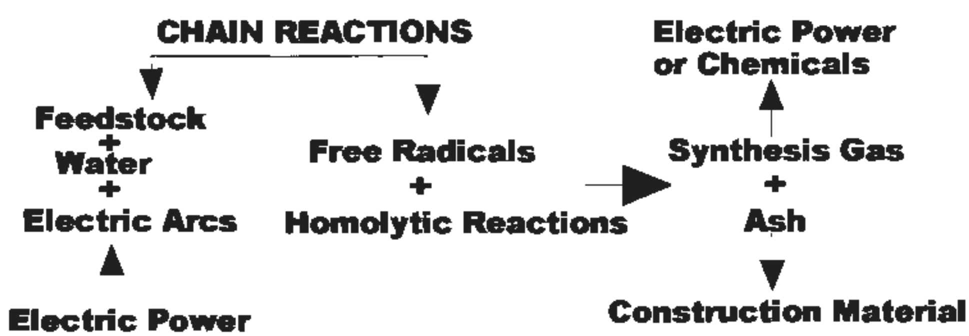
The process makes a high quality synthesis gas which can be used for power generation or for the production of chemicals such as methanol or ammonia. The high temperatures can potentially break down all large molecules such as dioxins.

Data on the gasifier are shown in Table 1. The gas composition from this run is shown in Table 2.

Table 1 - Skygas PDU Data

Feed	Wood Waste, 50% moisture
Feed rate	4 tons/hour
Duration of run	2.5 hr
Power input	1300 kW
Gas output	1,833 scf/m
Gas hhv	372 Btu/scf
Energy Balance - Energy In	
Wood	37.1 Mbtu/hr
Carbon	3.2 Mbtu/hr
Power	4.4 Mbtu/hr
Total	44.7 Mbtu/hr
Energy Balance - Energy Out	
Gas hhv	40.9 Mbtu/hr
Energy Recovery	91%
Potential power production @ 33% Efficient	3.95 kW
Net power gain ratio	3.0

The electric arcs operate in a steam atmosphere generating hydrogen atoms and hydroxyl radicals which give homolytic bond cleavage with larger molecules according to:



The Skygas venture includes MPM Technologies, a mining company that owns the technology (Spokane, WA., R. D. Little, 509 326 3443); Unitel Technologies, Inc., marketing and engineering; and USF Smogless S.p.A., (plant designing).

Table 2 - Skygas Composition (volume %)

Gas	Volume %
H_2	36.2
CO	57.6
CO_2	0
CH_4	438
Ethane	035
Butane	0.3
N_2	0.4
C6+	0.1
Total	100
H_2+CO	94.1

3.14 SOFRESID/CALIQUA (ANDCO TORRAX)

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Process: Updraft Slagging Air-Gasification of Municipal Wastes

PROCESS SUMMARY

The aim of this process is the gasification of MSW in two 8 ton/hour fixed bed slagging updraft gasifiers for the disposal of MSW [Bridgwater, 1993]. The resultant low heating value gas is used to fuel a conventional steam boiler for electricity production and district heating [Bridgwater, 1993].

In 1978, at NREL (then SERI), I suggested that one way of disposing of nuclear wastes, was to encapsulate them as a dilute solution in the copious slag that could be created in this or the Purox gasifier. In 1985 I visited the plant at Disneyland, constructed with $20 M of department of defense money to test this. The gasifier had operated satisfactorily, but ash had built up in the cyclone and not money was available for further testing, so the plant was dismantled.

While not currently in wide use, this process is technically very interesting because it can handle high mineral content biomass (like MSW) and is the only air/slagging biomass gasifier known to have been built. (See PUROX for oxygen slagging gasifier.) This report is abstracted from [Bridgwater, 1993]

DESCRIPTION

Background

The Sofresid Group is a management, engineering and construction group part owned by John Brown Engineering located in the UK (main shareholder). Caliqua is the heat and power division of Sofresid specializing in a number of heat and power applications including industrial and district heating plants, thermal electric power plants, refrigeration plants, electrical substations and thermal control systems.

The Caliqua gasification system is based on a 1968 patent by Torrax Systems (USA). Caliqua holds the Andco-Torrax license in Europe. Six plants shown below were constructed of which only one is now operating. This plant is owned and operated by Créteil Incinération Energie.

The plant at Créteil is shown in Figure 1. Process data is shown in Table 1.

- Créteil, France
- Disneyland, Florida, USA
- Grasse, France
- Japan
- Luxembourg
- Munich, Germany

PROCESS DESCRIPTION

Existing Process

A flowsheet of the existing process at Créteil is shown in Figure 1. Process data is shown in Table 1. This plant was engineered and constructed by Caliqua in 1979 exactly to the Andco-Torrax design but modifications proposed in 1987 are shown as broken lines.

The Créteil gasification plant consists of two identical process units each of 8 ton/hour capacity [Bridgwater, 1993]. Gasification air is preheated to 1000°C by steam heating coils, an oil burner and a natural gas burner [Bridgwater, 1993]. This reduces the oxygen concentration of the input air to the gasifier to approximately 11%. Electric heating has been tried but was not fully successful. The hot air is injected into the base of the gasifier through a series of 12 nozzles. Wastes are fed through the top of the reactor . Urban refuse is loaded through the top of the gasifier using a manually controlled grab. Hospital waste is delivered to site in closed skips which are automatically transported to the top of the gasifier by a monorail system. The skips are emptied directly into the gasifiers and returned to the hospitals for further use. During gasification, ash is converted to slag which is granulated using a water quench . The gasifier requires 150 m^3h^{-1} of water. Quench water is recycled and there is no wastewater from this plant.

The product gas from the gasifier leaves the gasifier at 1200°C and is burnt in a conventional combustor at 1250°C . Heat is recovered from the hot flue gases using a waste heat boiler. Ash is removed from the gas combustion chamber as slag . Gaseous combustion products from the boiler are passed through an electrostatic precipitator before discharge to atmosphere .

Steam is used for electricity production in a condensing steam turbine . Excess electricity is sold to the French national grid and waste heat from the turbine is recovered using a district heating scheme . Excess heat can be dissipated to atmosphere using a cooling coil .

FEEDSTOCKS AND CHARACTERISATION

The Caliqua plant is designed for the gasification of municipal solid waste. The waste is not pretreated before gasification.

PRODUCTS

The lower heating value of the feed material is reported to be 7.92MJ/kg . The product gas is combusted in a secondary combustion chamber as shown in Figure 1 (mean temperature 1250°C).

Slag is removed from the base of the gasifier and is granulated by water quenching . It is reported that the granulates are free of organic materials and may be used as filler material . The yield of slag is shown in Table 1.

PERFORMANCE

Calculations carried out based on a feedstock throughput of 7 ton/hour and a mean efficiency of 68% show that the process will yield an electric output of 1.6 MW and a heat output to the district heating network of 10.5 MW . Availability is estimated at 70%. The process efficiency, gas product yield, maximum and minimum throughputs, turn down ratio and system reliability are not reported.

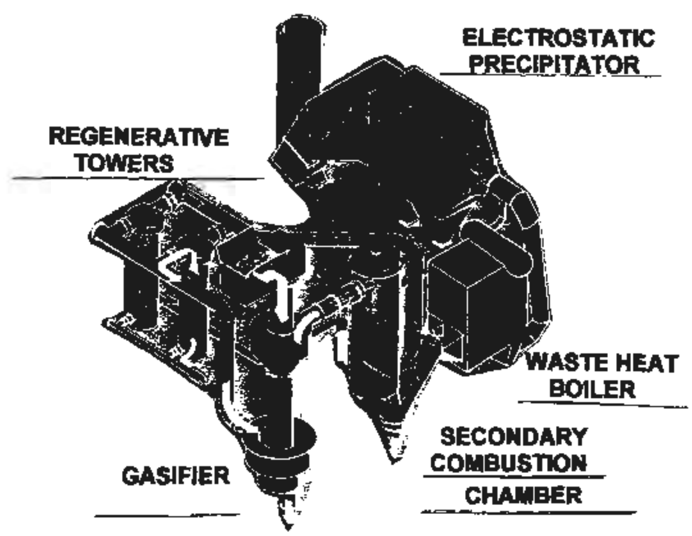

Figure 1 - Flowsheet of Sofresid/Caliqua (Andco Torrax process) MSW Gasification System at Créteil [Bridgwater, 1993]

The slag yield is less than10 kg/kg feed. This can be compared with the ash yield from an incineration plant of approximately 30%. It is reported that the cooled ash is free of organic materials and to be glass like . In addition, heavy metals are "locked in" the slag and can not be dissolved out.

COSTS

Capital Costs

The turnkey capital cost of the Andco-Torrax gasification plant at Créteil was FF100 million (1979-80), or (at 1997 0.175Fr/$) $17.5M. This includes the cost of specialized foundations due to the siting of the plant on marshland. This cost includes all equipment and commissioning.

In 1987, the mean selling price of electricity was 190 F/MWh (£1.90/MWh) . The selling price of heat is proportional to the selling price of natural gas . In 1986, heat was sold at two prices. From April to September 1986, the mean selling price of heat to consumers was 110% of the gas price . From October to March, the mean selling price of heat to consumers was 135% of the gas price (price of natural gas in 1986 was 100 F/MWh) . This equates to $5.347/GJ. The actual cost of the raw product gas is not reported.

Table 1 Process Data for Caligua plant at Créteil

Process	Updraft, Slagging, Air, MSW Gasifier
Main feedstock	MSW
Main product	Low heating value gas
Main product use	Steam raising for district heating and electricity production
Steam yield	5.3 kg/kg feed
Primary hy-product	none
Feedstock throughput (daf)	8128 kg/h
Reactor type	Fixed bed updraft
Primary reactor operating pressure	1 bar
Primary reactor operating temperature	1300-1400 °C
Reactant	Hot air
Reactant input rate	6000 m^3/h
Solid waste flowrate	10 kg/kg daf feed

Table 2 - Summary and Balance of Operating Costs and Incomes £/year*

Income		
	Incineration fees	740 400
	Heat sold	1 198 000
	Electric power sold	269 100
	Slag sold	30 000
	Total	2 237 500
	at 90% availability	2 013 700
Expenses		
	Gas	350 100
	Water	20 000
	Electric power	20 000
	Salaries	550 000
	Insurance	71 000
	Miscellaneous	161 500
	Plant maintenance	330 000
	Network maintenance	100 000
	Total	1 602 600
	Net income £/year excluding capital cost	**411 100**

Income is also obtained in the form of a tipping fee and the sale of iron/slag . The current (September 1992) tipping fee for hospital waste in Paris is FF1000 - 1100 /tonne. It is estimated that the annual income from the sale of iron and slag in 1986 would be FF300,000 (see Table 4) .

Operating Costs

A summary of the operating costs and incomes is shown in Table 4.

Product or Production Costs

REFERENCES

[Bridgwater, 1993] Bridgwater, A. V. and Evans, G. D., "An Assessment of Thermochemical Conversion Systems for Processing Biomass and Refuse", Report, Energy Technology Support, (ETSU), ETSU B/T1/00207/REP, 1993.

[Anon, 1987] Anon., "Caliqua - Siduic Proposal for Improving a Slagging Pyrolysis Process of Municipal Wastes - Technical and Economic Memorandum", European Economic Community, Energy Management, 1987 Energy Demonstration

3.15 Sur-lite

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Telephone: 562 693 0796

Fax: 562 693 7564

E-Mail: SUR-LITE@deltanet.com

Process: Fluidized Bed for Gas, Steam

The Surlite Corporation specializes in all forms of combustion. They manufacture a line of modular, skid mounted fluidized bed gasifiers capable of converting biomass and wastes into clean combustible gas for boiler firing, industrial drying and firing of kilns. Sur-Lite bas constructed a 1.5 Mbtu/hr pilot gasifier available for testing. They bave successfully gasified rice hulls, shredded tires, dried dairy manure, dried sewage sludge and RDF. They have built a special fluid bed gasifier for cotton gins and lime kilns available in size from 10 to 80 Mbtu/hr (0.6 to 5 tons/hr).

3.16 THERMOCHEM, INC. (Manufacturing and Technology Conversion International, Inc. (MTCI))

Contact: Ravi R. Chandran (Vice President of Engineering)

Address: MTCI, 6001 Chemical Road, Baltimore, MD 21226

Telephone: (410) 354-0420 Fax: (410) 354-0471 E-mail: RChandran@mtcionline.net

Process: PulseEnhanced™ Steam Reforming

PROCESS

In cooperation with the U.S. Department of Energy (DOE), California Energy Commission, Environmental Protection Agency and private companies, MTCI and its affiliate, ThermoChem, Inc., have developed a steam-reforming technology that is uniquely capable of processing a wide spectrum of organic feedstocks to produce a hydrogen-rich, medium calorific value reformate gas. The MTCI/ThermoChem Steam Reformer can be used for the conversion of Refuse Derived Fuel (RDF), sewage sludge, paper mill sludge (primary, secondary or recycle mill rejects), biomass, coal, scrap tires, hazardous waste, pulp mill spent liquor or any other materials containing organics.

The PulseEnhanced™ Steam Reformer uses a patented indirect heating method that permits the steam reforming of organic-rich materials into a medium calorific value product gas (H_2 and CO) which can further be converted to methanol or hydrogen or used as a fuel in fuel cells, gas turbine combined-cycles and gas piston engines (including Diesel). The indirect heating method involves modular pulsating heaters in a bubbling fluid-bed reformer. The process temperature is relatively low and this together with the reducing environment, inhibits the formation of chlorinated dioxins and furans as well as the condensation of metals on fly ash normally encountered in conventional incinerators. This technology is very versatile and is applicable to many different fields of use.

INTRODUCTION

MTCI is a technology development company located in Baltimore, Maryland and has developed many advanced energy conversion, waste treatment and air pollution control processes. ThermoChem, Inc., is also located in Baltimore and markets, engineers and commissions the proprietary systems developed by MTCI.

A simplified schematic of the PulseEnhanced™ Steam Reformer system is shown in **Figure 1**. It consists of a fluidized bed reactor that is indirectly heated by multiple resonance tubes of one or more pulse combustion modules. Feedstock such as biomass, coal, sludge or spent liquor is fed to the reactor which is fluidized with superheated steam from a waste heat recovery boiler. The organic material injected into the bed undergoes a rapid sequence of vaporization and pyrolysis reactions. Higher hydrocarbons released among the pyrolysis products are steam cracked and partially reformed to produce low molecular weight species. Residual char retained in the bed is more slowly gasified by reaction with steam. Product gases are routed through a cyclone to remove bulk of the entrained particulate matter and are quenched and scrubbed in a venturi scrubber. A portion of the medium calorific value product gases is supplied to the pulse combustion modules and combustion of these gases provides the heat necessary for the indirect gasification process [Durai-Swamy, 1991, Mansour,1993].

The MTCI technology overcomes the limitations of both the oxygen-blown partial oxidation and the two-stage circulating solids gasification systems. In the MTCI process, the feedstock is fed to a single fluidized bed vessel and reacted with steam to generate a hydrogen-rich product gas. The use of a fluidized bed offers an ideal environment for effecting the endothermic steam-reforming reaction with the heat supplied indirectly through heat transfer surfaces that are formed from the resonant section of a pulse combustor immersed within the fluid bed. These pulsations translate into improved heat transfer rates (as much as 3 to 5 times) through the fire tubes and into the fluid bed. This has been termed ac heat transfer by Dr. T.B. Reed. Using the above configuration, the MTCI process has generated a synthesis quality product gas from a wide spectrum of feedstocks including biomass, coals, municipal waste, refuse-derived fuel (RDF), industrial sludges, and spent liquor from the pulp and paper industry, all without the use of air or oxygen. The product gas is free of both diluent nitrogen and combustion-generated CO_2. The complete reforming process is accomplished using only a single vessel, and no circulation of hot solids is needed. The combustion process utilizing clean product gas eliminates the need for flue gas treatment from the combustors.

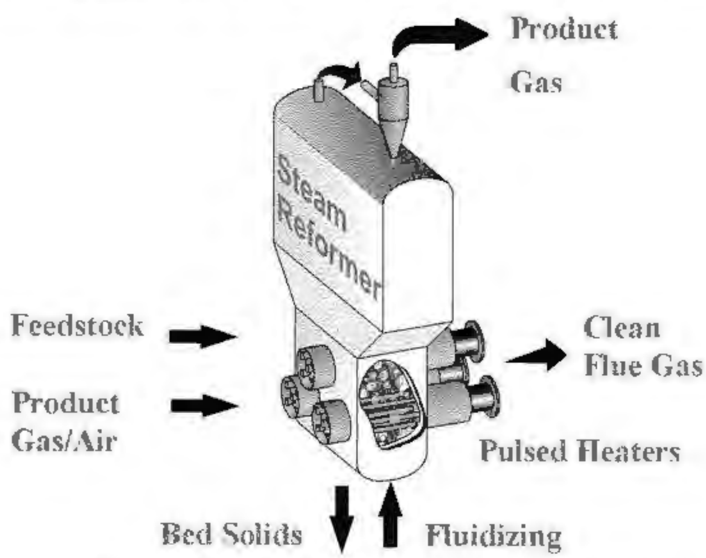

Figure 1: PulseEnhanced™ Steam Reformer

The technology was initially introduced under the DOE/SBIR program in 1983. The initial scope of the technology development was for steam reforming of biomass feedstocks. The consistent support by the

Department of Energy, the Pulp and Paper Industry, and some EPA-SBIR grants has in a few years moved the technology for energy and process chemical recovery of spent liquors and energy recovery from mill waste streams and waste biomass materials to pilot-scale field tests at the 50 tons/day size.

The first MTCI/ThermoChem demonstration plant was built in 1992 at the Inland Container Corporation recycle paper mill in Ontario, California and operated on sludge containing short fiber rejects and plastics. The demonstration plant had a nominal capacity of 12 tons per day with one pulsed heater module. This demonstration established that the heater module was very reliable with availability over 99 percent of the time. This demonstration unit is now available at MTCI's Baltimore facility where over 5,000 hours of testing on various feedstocks have been conducted. It is noteworthy that this plant was permitted in Southern California.

In 1995, MTCI conducted a successful demonstration of a 50 tons per day PulseEnhanced™ Black Liquor Steam Reformer at the Weyerhaeuser kraft pulp mill in New Bern, North Carolina.

ThermoChem and MTCI have also successfully carried out several process demonstration campaigns with Low-Level Mixed Waste (LLMW) surrogates in a steam-reforming process development unit. This included a 750-hour continuous test run. The test results indicated essentially total (>99.9999%) destruction of RCRA and TSCA hazardous halogenated organics, significant levels of volume reduction (up to 1,000 to 1), and the retention of radionuclides in the volume-reduced solid residues. The overall system offers an environmentally safe, non-incinerating, cost-effective, and publicly acceptable method of processing LLMW. An evaluation commissioned by the U.S. Department of Energy's Mixed Waste Focus Area rated this steam-reforming technology as the No. 1 technology out of 23 candidate technologies that are alternatives to incineration for destruction of hazardous organic wastes [Schwinkendorf, 1997].

TEST RESULTS

Early system tests were performed in a bench-scale unit using three different biomass feeds: pistachio shells, wood chips, and rice hulls; two different sludge waste products from a recycle paper mill (the wastes differed primarily in their plastic content); a Kraft mill sludge, RDF; and dried Municipal Sludge Wastewater (MSW). The waste paper sludge was obtained from a mill located in Northern California. The sludge fraction was composed of short fiber and plastic reject material that is recovered from a clarifier. These sludge wastes were representative of high moisture waste materials that are generated in similar mills located throughout the United States.

Table 1 summarizes the operating conditions for the various test runs in the bench-scale unit. Temperatures were varied over the range of approximately 1215°F to 1450°F. Steam-to-biomass ratios varied from approximately 0.75 to 2.6. Test run duration typically ranged from 4 to 10 hours. No process operating problems were encountered for any of the runs, including those with rice hulls that have a high ash content and low ash fusion point.

The resultant gas compositions from the various biomass waste feedstocks are summarized in **Table 2**. The methane content appears to be relatively constant (5 to 12%) over the range of feeds and processing conditions tested. Higher hydrocarbons show a decreasing trend with increasing temperature and a concomitant increase in hydrogen yields. The ratio between carbon monoxide and carbon dioxide appears to be relatively constant. The dry gas heating value typically range

In another project sponsored by Southern California Gas Company to evaluate the low NO_x potential of natural gas-fired pulse combustors, MTCI tested burners in three different configurations: a pulse burner (0.76 to 5.58 million Btu/hr firing rate range) retrofitted to a Cleaver-Brooks boiler and two versions of a pulse combustor from 2 to 9 million Btu/hr including a 72-tube heater/heat exchanger bundle of the type used in the steam-reforming process. In all the cases, the NO_x emissions measured were less than 30 ppm @ 3% O_2. Emissions data from a pilot-scale 72-tube heater/heat exchanger bundle **(Figure 2)** that had already accumulated more than 5,000 hours of operation were measured by several instruments and organizations.The California State Polytechnic University, Pomona, through the Engineering Interdisciplinary Clinic, independently verified the emissions and efficiency data. In one instance, Southern California Gas Company also independently verified the emissions data.

TABLE 1 - Operating And Process Conditions For Biomass Waste Test Runs

Feedstock	Temp. (° F)	Average Feed Rate (lb/h)	Steam Rate (lb/h)	Steam To Biomass (lb/lb)	Total Feed (lbs)
Pistachio Shells	1,317	35.5	26.0	0.7	337.0
Pistachio Shells	1,216	30.6	31.5	1.0	115.3
Wood Chips	1,286	22.9	31.4	1.4	205.7
Rice Hulls	1,326	30.8	26.0	0.8	185.5
Recycle Paper Mill Sludge	1,250	17.6	36.5	2.1	118.8
Kraft Mill Sludge Waste	1,250	17.6	36.5	2.1	299.6
RDF (sand bed)	1,450	11.0	29.0	2.6	66.0

d from 370 to 448 Btu/scf.

APPLICATIONS

The PulseEnhanced™ Steam Reformer technology is very versatile and is applicable to many different fields of use. The initial target markets for commercialization are the pulp and paper industry and the biomass power generation sector.

To address the need for small (5 kW_e to 5 MW_e), modular biomass power systems that are fuel-flexible, efficient, simple to operate, cost-effective and environmentally benign, MTCI has developed two advanced concepts. One is for near term market penetration and involves the integration of a thermochemical reaction subsystem with a gas turbine subsystem to generate electricity from biomass. The other is the integration of a PulseEnhanced™ Steam Reformer with a Fuel Cell. This is termed the ThermElectroChemical System (TECS). MTCI envisions this to be the premier green power system but a long-term solution due to the current high cost of fuel cell stacks.

ADVANCED CONCEPT I

An advanced thermochemical reaction subsystem typically includes a PulseEnhanced™ Steam Reformer, a steam superheater, a gas cleanup train, and a heat recovery steam generator (HRSG). The gas turbine subsystem normally includes an air compressor, a gas turbine with combustor, and an electric generator. Here it also includes a fuel gas compressor to compress the gas from near atmospheric pressure to the inlet pressure required to flow through a control valve into the gas turbine combustor. The innovation here corresponds to process and thermal integration to maximize performance, minimize emissions and render economics favorable for commercialization. The novel features are:

- Gas cleanup occurs prior to combustion and this greatly reduces the volumetric flow through the gas cleanup train and in turn its cost. This also protects the gas turbine and minimizes emissions.
- The system employs proven technologies for near-term commercialization.

TABLE 2 - Gas Compositions and Product Yields for Biomass and Mill Sludge Tests Conducted in Pulse-Enhanced Indirect Steam Reformer

COMPOSITION (Vol.%)	PISTA-CHIO SHELLS	PISTA-CHIO SHELLS	WOOD CHIPS	RICE HULLS	RECYCLED MILL FIBER WASTE	RECYCLED WASTE PAPER W/PLASTIC	KRAFT MILL SLUDGE	RDF SAND BED	MSW SAND BED	MSW LIME-STONE BED
H2	37.86	35.04	48.11	42.83	38.86	50.50	52.94	45.54	55.21	54.40
CO	18.84	23.43	22.91	19.67	23.34	19.26	11.77	25.26	28.10	25.46
CO2	28.73	25.20	20.18	24.40	23.27	20.10	21.94	14.51	5.95	5.66
CH4	10.65	11.31	8.32	11.56	8.31	8.42	8.95	8.30	5.00	5.86
C_2	3.92	5.02	0.48	1.54	6.40	1.72	3.00	6.38	5.74	8.62
HHV, Btu/scf	370	406	329	367	412	364	372	418	374	448
TEMP. °F)	1317	1216	1286	1326	1250	1326	1250	1450	1410	1306
Yield (%c)	94.1	92.1	93.0	N/A	86.8	N/A	56.0	83.6	93.7	83.8

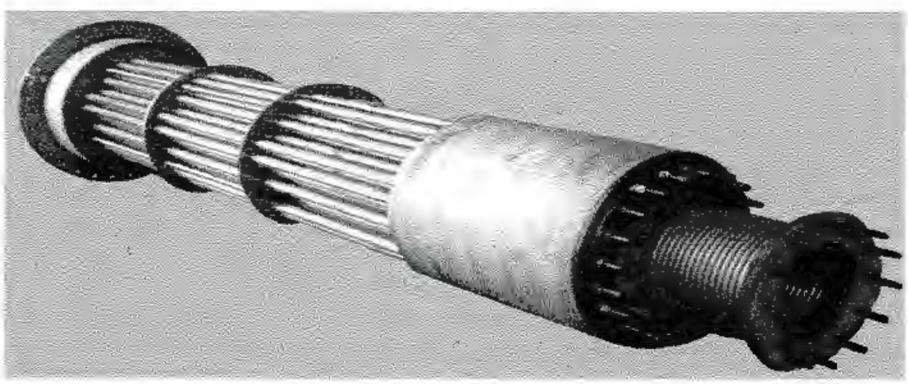

Figure 2 - Tube Pulse Heater/Heat Exchanger Bundle

The fuel gas input to the gas turbine for power generation is maximized and the fuel gas input to the pulse combustor for supplying the endothermic heat of steam reforming reactions is minimized. This is accomplished by recuperatively heating part of the turbine exhaust and supplying that as oxidant to the pulse combustor/heater. Here, the pulse heater exhaust first transfers heat to the turbine exhaust stream on its way to the pulse heater and then preheats the compressed air supplied to the gas turbine combustor.

Surplus thermal energy in the flue and fuel gas streams is recovered as superheated steam for injection into the gas turbine to boost power output. This eliminates the need for a bottoming steam cycle and the associated cost. The steam flow rate is on the order of 5% of the total mass flow through the gas turbine and is in the realm of current commercial offerings featuring steam injected gas turbine or STIG. The steam addition in the high temperature cycle improves power generation efficiency.

The thermochemical reaction subsystem is feedstock flexible and can steam reform a wide variety of biomass such as wood and wood wastes, agricultural residues, energy crops, forest residues, animal wastes, and municipal wastes. This broadens the market appeal, the security of feedstock supply and commercialization scope.

A schematic of the reference configuration of the integrated system is shown in **Figure 3** The system comprises the following major subsystems [Chandran, 1999]:

- Biomass handling and feeding subsystem,

  PulseEnhanced™ Steam Reformer,
- Steam superheater,
- Fuel gas cleanup train containing
  - ➢ Venturi/gas cooler
  - ➢ H_2S Absorber or Ammonia absorber (optional – not shown)
- Fuel gas compressor,
- Heat Exchangers I and II, boiler and heat recovery steam generator (HRSG),
- Bed solids handling and storage subsystem; and
- Gas Turbine power generation subsystem.

This arrangement maximizes the energy input to the gas turbine cycle, minimizes fuel gas use for pulse heating and avoids the need for a bottoming steam cycle.

Many computer simulations were carried out to evaluate performance, emissions and economics. The feedstock selected was wood. In order to compare with the results of the Integrated Gasification Combined Cycle Studies performed by the National Renewable Energy Laboratory [Craig, 1996: Bain, 1997; Craig, 1995], the wood analysis corresponded to Wisconsin Maple [Craig, 1996] with 38% moisture as received and a Higher Heating Value (HHV) of 19.715 MJ/kg dry (8,476 Btu/lb dry). Two nominal system sizes, namely, a 5 MW_e and a 1 MW_e were investigated. The ambient conditions were assumed to correspond to the standard conditions stipulated by the International Standards Organization (ISO).

The nominal design parameters of the steam reformer are furnished in Table 3. A Rolls-Royce Allison KB5 gas turbine was selected for the nominal 5 MW_e system and a Solar Turbines Saturn 20 was selected for the nominal 1 MW_e system.

Table 3: Nominal Design Parameters

Steam Reformer	
Feedstock	Wood
Fluid Bed Temperature	802°C or 1,475°F
Freeboard Pressure	153 kPa or 7.5 psig
Fluidization Velocity	0.46 m/s or 1.5 ft/s
Fluidization Medium	Steam

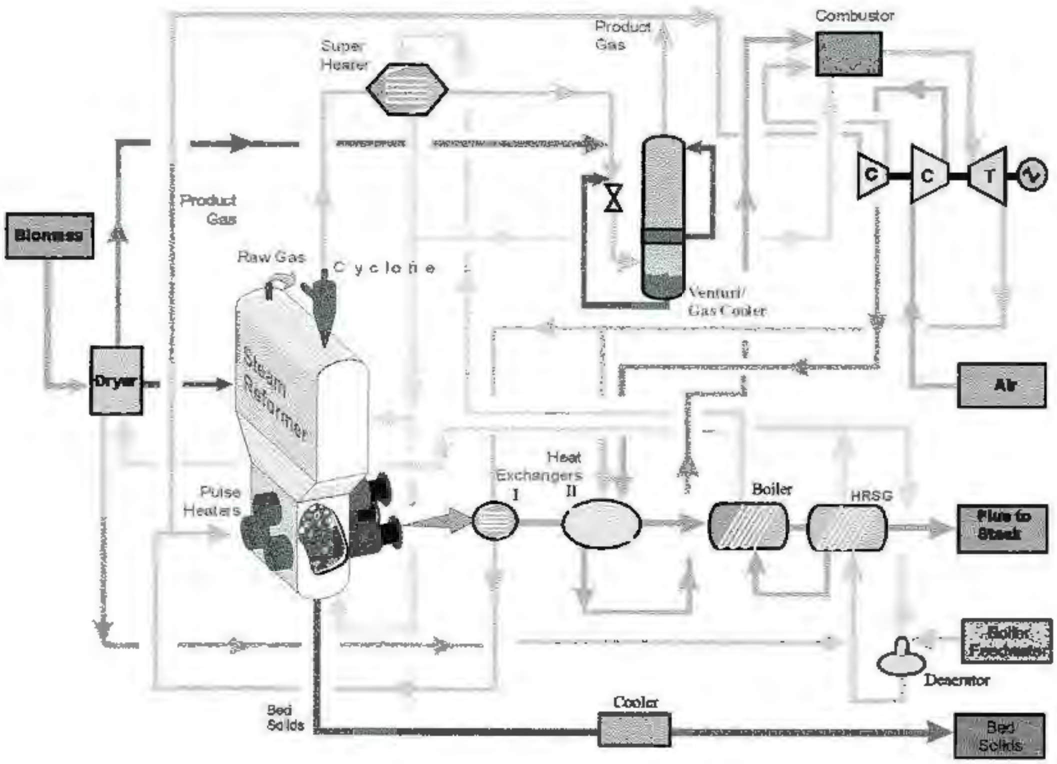

Figure 3: Schematic of the Integrated Steam Reformer/Gas Turbine System for Biomass Power Generation

Computations indicated the nominal dry wood throughput to be 76.2 tonne/day (84 ton/day) and that two 253-tube pulse heaters are required for the nominal 5 MW_e system. The corresponding numbers for the nominal 1 MW_e system were 21.77 tonne/day (24 ton/day) and two 72-tube pulse heaters. The primary constituents of the fuel gas after the gas cleanup train turned out to be H_2, CO, CO_2, H_2O and CH_4. The fuel gas composition on a volumetric basis corresponded approximately to 50% H_2, 23% CO, 15% CO_2, 9.5% H_2O, 2.3% CH_4 and traces of C_2H_4, C_2H_6, NH_3 and H_2S. The HHV of the fuel gas was about 9.88 MJ/scm (265 Btu/scf).

Table 4 provides a summary of the system performance. The gas turbine net power shown corresponds to gas turbine generator output minus the inputs for the air and fuel gas compressors. Prime mover mechanical efficiency of 98.5% and generator efficiency of 98% were assumed for the analysis. The plant power consumption accounts for power inputs to biomass handling and feeding subsystem, pumps and instrumentation and control subsystem. The turbine power outputs, especially with the Rolls-Royce Allison KB5, significantly exceed the nominal ratings with natural gas. This is attributed to mass flow augmentation by fuel gas (heating value lower than that for natural gas) and steam. This may lead to balance and stability problems with the compressor-turbine subsystem. Additional development will probably be needed to configure a gas turbine generator package for power generation from biosyngas. This will include arrangement of air compressor, fuel gas compressor, gas turbine and generator all on one shaft.

The component and piping heat losses are tantamount to about 8% of the energy input in biomass in the case of the 5 MW_e system and about 12% of the energy in biomass for the 1 MW_e system. The net electrical efficiency turned out to be 26.6% for the 5 MW_e system and 21.5% for the 1 MW_e system, both on HHV basis. These values are higher than those of conventional and current advanced small biomass power systems. The emissions projected for the integrated systems are also listed in Table 4. The emissions are listed on the basis of lb/MMBtu to enable comparison with the proposed new environmental regulations (onetenth of New Source Performance Standards or 1/10 NSPS). Due to steam reforming and fuel gas cleanup, the emissions are all low and are significantly lower than the proposed regulations.

Table 4: Performance Summary

Nominal System Size		**1 MW**	**5 MW**	
Biomass Processing Rate	Tonne/day dry	21.77	76.20	
Gas Turbine Gen Set		Saturn 20	KB5	
Gas Turbine Net Power	MW_e	1.136	4.817	
Plant Power Consumption	MW_e	0.066	0.193	
Net Power Export	MW_e	1.070	4.625	
Specific Power Output	MWh/tonne dry	1.179	1.457	
Net Electrical Efficiency	% HHV basis	21.5	26.6	
	% LHV basis	23.1	28.5	
Emissions:				1/10 NSPS
SO_2	Lb/MMBtu	0.040	0.050	0.12
CO	Lb/MMBtu	0.030	0.030	
NO_x	Lb/MMBtu	0.030	0.050	0.06
VOC	Lb/MMBtu	0.001	0.003	
Particulate	Lb/MMBtu	<0.0001	<0.0001	0.003

An economic assessment was performed utilizing component specifications, the methodology outlined in the Electric Power Research Institute Technical Assessment Guide [TAG, 1993], vendor quotes and in-house cost database. A fuel price of $33.07 per dry donne ($30/dry ton) for wood was assumed based on resource assessment data. The levelized cost of electricity (COE) for nth plant was estimated to be 9¢/kWh for the nominal 5 MW_e size and 14.5¢/kWh for the nominal 1 MW_e size. These are based on U.S. labor rates and apply to the U.S. market. The electricity cost is quite sensitive to fuel price; for instance, COE drops to 6.8¢/kWh with zero fuel cost for a 5 MW_e system. The steam reformer is fuel flexible and can also process feedstocks with a tipping fee. This together with the fact that the electricity prices for commercial and residential markets in selected parts of the U.S. (New England States, California, Hawaii, etc.) exceed 10¢/kWh provides a significant near-term market potential for this technology.

ADVANCED CONCEPT II

A simplified block-flow diagram of the second advanced concept is shown in **Figure 4**. It

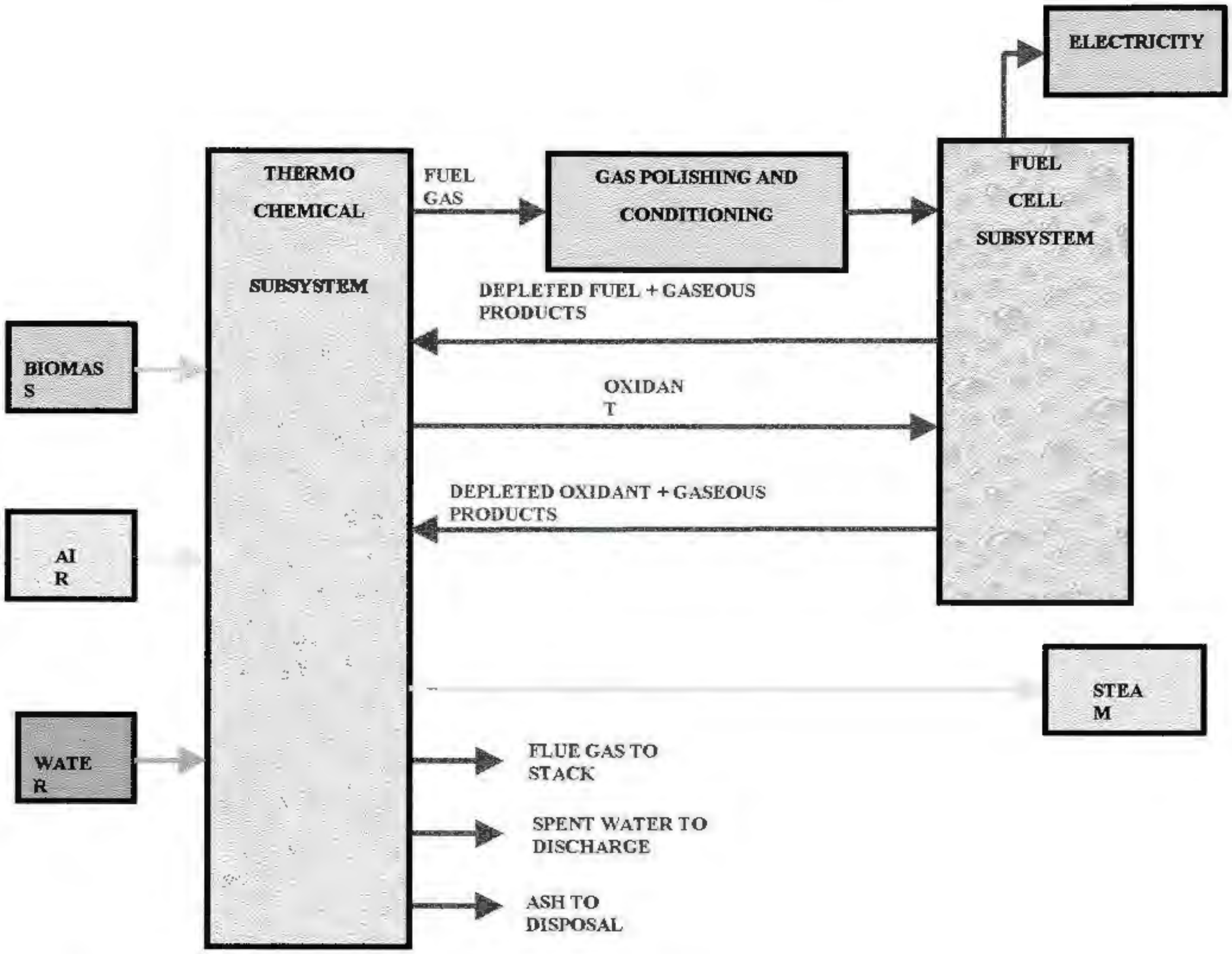

Figure 4: A Simplified Block-Flow Diagram Of The Thermoelectrochemical System

integrates a thermochemical reaction subsystem with a fuel cell subsystem to generate electricity and steam from biomass. The PulseEnhanced^{TM} Steam Reformer generates a hydrogen-rich, medium calorific value fuel gas that is electrochemically oxidized in the fuel cell to generate electricity. The thermochemical reaction subsystem typically includes a PulseEnhanced^{TM} steam reformer, gas cleanup train, heat recovery steam generator (HRSG) and air heater. Part of the product gas generated by the steam reformer is used in the pulse heaters and the remainder is sent to the fuel cell subsystem for power generation. The fuel gas generated by the steam reformer, most likely, will have to undergo one or more gas polishing and conditioning steps in order to meet the fuel gas cleanliness requirements of the fuel cell. The fuel cell subsystem typically includes fuel processor, fuel cell power section and power conditioner. The fuel processor could simply be a pass-through/delivery device if hydrogen is the fuel or could have sulfur

polisher, reformer, shift reactor, particulate filter, and burner if a conventional gaseous fuel (natural gas, propane, butane, etc.) is used. Obviously, the fuel cell subsystem package varies with fuel cell type and application [Hirschenhofer, 1994; Fuel Cell, 1998; Fuel Cells, 2000].

Studies were carried out under the sponsorship of the U.S. Department of Energy Small Business Innovation Program to integrate a PulseEnhancedTM steam reformer - which could convert a wide spectrum of biomass fuels into a reformate gas – with three different fuel cell types namely, Phosphoric Acid, Molten Carbonate and Solid Oxide. Many computer simulations were performed [Chandran, 1999]. The optimum system was found to be a steam reformer innovatively integrated with a solid oxide fuel cell (SOFC) to generate electricity. The system integration concepts employed and the engineering/economic analyses have shown that the TECS is capable of higher efficiency, lower emissions, lower capital cost and reliability well beyond what could be achieved by any of the conventional and emerging heat engine based power systems. A market entry strategy has been identified to exert market pull for mass production of fuel cell stacks and thereby reduce costs. Siemens Westinghouse has labeled this near team opportunity as the one that will provide the SOFC technology with the "escape velocity" it needs for expanding penetration of the SOFC in the commercial market for all applications.

3.17 COGENERATION

The economics of biomass gasification for co-generation have been evaluated by Dr. Eric Larson of Princeton University [Larson, 1997; Consonni, 1998; Larson, 1998] for a 100-MWe scale integrated black liquor gasifier with a combined cycle power island. As can be seen in **Figure 5**, gasification-based black liquor processing at a kraft pulp mill produces very attractive power generation costs compared to those for traditional Tomlinson-based systems. The gasification-based power plant generates double to triple the amount of electricity for the same black liquor throughput, thus lowering the total cost of electricity generation to approximately half that of the Tomlinson-based technology. Also, Dr. Larson's study clearly indicates that ThermoChem's indirectly heated steam reformer island would produce the lowest electricity

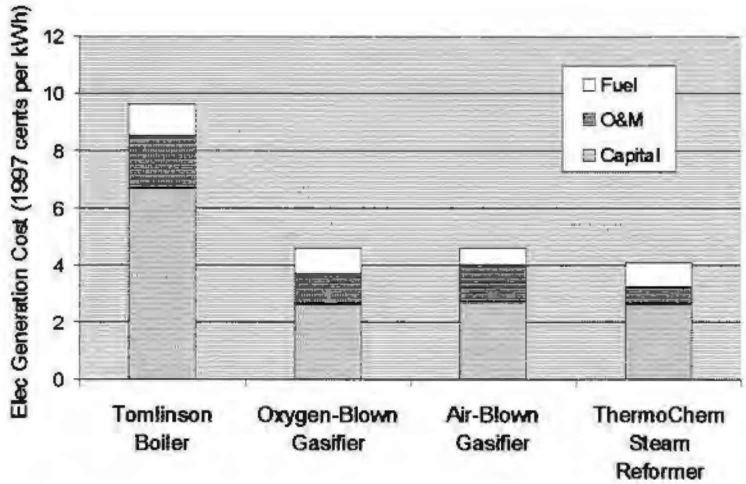

Figure 5: Cost of Electricity Generation [Larson, 1998]

generation cost of all cases studied. READINESS

The MTCI/ThermoChem technology is ready for full-scale operation at power generating sites for biomass gasification service. Private industry clients have already chosen the steam reformer for gasification ofwaste pulping liquor (Georgia-Pacific and Sappi) at the 200 tons per day capacity level.

Extensive risk analyses have been completed by clients such as Georgia-Pacific, and insurer's due diligence is in progress with an international carrier. Stone and Webster's professional engineers have reviewed the system extensively. As a result, they are prepared to provide process warranties for complete systems. Both Stone and Webster and Industra Engineers have agreed to participate in selective build, own and operate (BOOT) projects.

In addition, U.S. Department of Energy (DOE) and other funded developments have demonstrated the steam reformer's robustness on a wide variety of dry biomass and coal feedstocks at the 50 tons per day range. Many more fuels have been successfully processed at the pilot scale in MTCI/ThermoChem's Baltimore research and training facility (**Figure 6**) which is in full operation today.

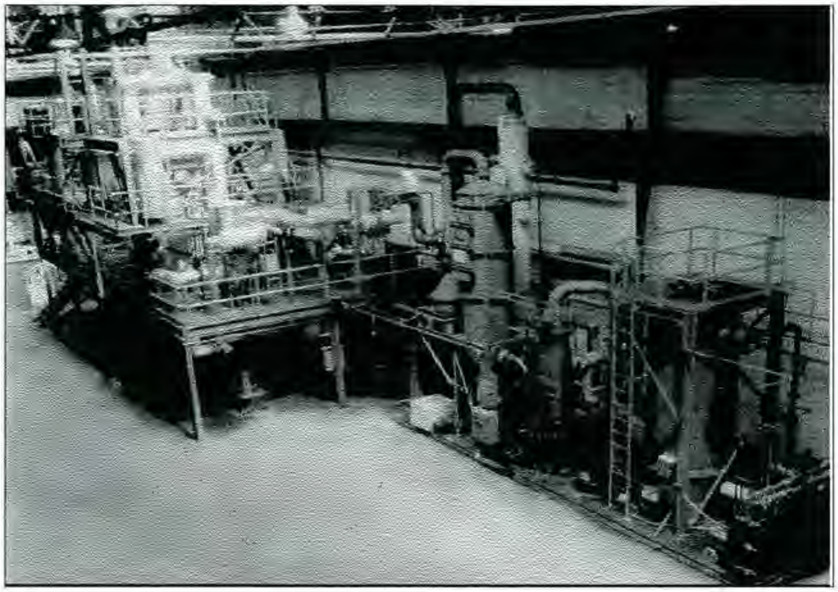

Figure 6: MTCI/Thermochem Research And Training Facility

Endorsements of the technology as a viable process for specific installations have been received from Georgia-Pacific, Weyerhaeuser, Sappi, Beloit Pulping and others.

CURRENT STATUS AND FUTURE PLANS

MTCI / ThermoChem have three pilot units for testing a wide variety of feedstocks in the steam reformer. Pilot tests have been conducted for the Energy Department and commercial clients on mixed waste, a variety of spent liquor types from numerous pulp and paper mills, and such biomass feedstocks as grass pellets, sawdust, wood chips, and others. The steam reformer has demonstrated capability to handle almost any carbonaceous material, to destroy complex organic chemicals in the form of hazardous wastes, and to tolerate and separate out non-process elements, such as silica, that would foul or create erosion in combustion based systems.

The MTCI process is being actively considered for recovery of chemicals and energy from wastes generated in the pulp and paper industry as well as other wastes currently being landfilled or burned in combustors, such as animal waste. It was rated the best technology for volume reduction of mixed wastes in DOE nuclear facilities. Applications for energy recovery from biomass and municipal waste are being developed. ThermoChem and MTCI, under a DOE grant and private sector funding, are building and testing a scaled up 253-tube heater for steam reforming spent liquor and coal and other feedstocks. Engineering studies are underway with commercial clients for commercial spent liquor units in the U.S. and South Africa.

Development is underway for projects to steam reform wood chips and chicken litter in the U.S. and overseas. Studies are beginning to assess the economics and performance of the steam reformer in conjunction with gas turbines or fuel cells. Pilot or prototype tests of these applications are planned in 2000 and 2001.

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3.18 TPS Termiska Processer AB (Studsvik Energiteknik AB, ARBRE)

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Process: Major CFB gasifier manufacturer for IGCC, Greve plant in Chianti, IT, IGCC Brazil, UK

TPS Termiska Processer AB (formerly part of Studsvik Energiteknik AB) is a privately-owned R&D company based in Sweden. The company has 45 employees and a turnover of $7M per year. The company works in the field of energy and environmental process research and technology development. Commercialization of the technologies developed by TPS is normally through licensing to or joint ventures with experienced engineering companies.

On October 9, 1996, I visited Studsvik with a team of Swedish Consultants studying fluidized bed combustion and gasification for NUTEK, a Swedish governmental agency helping evaluate the Swedish energy program. The following information comes from that trip and from three earlier reviews [Kaltschmitt, 1996, Rensfelt, 1991, Rensfelt, 1997].

DESCRIPTION

Background

Studsvik Energy was a research and development company conducting R&D on energy conversion processes involving solid fuel, systems for heat distribution, recovery of waste heat and associated material problems [Kaltschmitt, 1996] . During the first half of 1992, Studsvik Energy was owned by Vattenfall (a Swedish utility). As of 1st July, 1992, Studsvik Energy became a separate company named TPS (Thermal Process Studsvik).

Initial gasification work included bench scale studies which led to the construction of a 2.5 MW_{th} (500 kg/h nominal) wood and peat fueled pressurized (10-30 barg) fluidized bed gasification plant (MINO process) financed by the Swedish State Energy Agency at Studsvik in 1983 [Kaltschmitt, 1996] . The aim of this process was to produce a low to medium heating value gas depending on whether oxygen or air was used in the process.

The primary gasifier was based on bubbling fluidized bed technology with an operating temperature of between 700 and 900°C. The gas produced from the MINO process contained condensable tars which were treated catalytically in a secondary reformer where the temperature was raised to between 850 and 1000°C by additional oxygen injection. Test work on the MINO pilot plant showed that the catalyst (nickel on an alumina carrier) was an efficient converter of tars, minimizing the consumption of oxygen by the secondary reformer. The tars were converted into useful gas components thereby increasing the process efficiency and avoiding downstream heat recovery equipment fouling [Kaltschmitt, 1996] . The last test performed under the MINO project was in 1986 and the pilot plant is currently mothballed.

The Studsvik atmospheric circulating fluidized bed gasifier was a development of an earlier design of a fluidized bed combustor. The first $2MW_{th}$ pilot scale gasifier designed for the production of a low heating value gas (4-7 MJ/m^3) from reactive fuels such as biomass, RDF and lignite was operated in 1986 and test programs were carried out testing bark and industrial waste in that year. The gasifier performed well providing a high char conversion efficiency [Kaltschmitt, 1996] . In 1987, due to a growing interest in diesel power electricity generation via gasification, a circulating fluidized bed hot gas cracker to remove tars from the raw product gas and a diesel engine were installed downstream of the gasifier [Kaltschmitt, 1996] . The CFB cracker was a development of the catalytic tar cracking method using dolomite developed in the Studsvik laboratories [Kaltschmitt, 1996] . Laboratory studies at Studsvik had shown that effective catalytic tar cracking could be obtained with a simple catalytically active material such as dolomite at atmospheric pressure and at temperatures between 800 and 900°C [Kaltschmitt, 1996] . This laboratory work is continuing at present. Operation of the combined gasifier/cracker/engine system started at the end of 1987 [Kaltschmitt, 1996] .

Two $15MW_{th}$ (input) Studsvik RDF fueled circulating fluidized bed gasifiers (without secondary cracking reactors) have been installed in Greve in Chianti by Aerimpianti SpA [Kaltschmitt, 1996] . These were undergoing acceptance tests in June 1992. The gasifiers produce a gas for combustion in conventional steam boilers. The gasifiers were built under license by Ansaldo Aerimpianti. A full description is given above.

PROCESS SUMMARIES

The aim of this process is the gasification of woody biomass or municipal solid waste in an atmospheric circulating fluidized bed gasifier for the production of a fuel gas for use in a duel fuel engine, a gas turbine or as a boiler/furnace/kiln fuel [Rensfelt, 1991]. A secondary circulating fluidized bed reactor cracks any tars in the raw product gas. A pilot scale plant with a thermal output of 2 MWth has been developed consisting of a circulating fluidized bed gasifier, circulating fluidized be cracker to remove tars from the gas and a turbo-diesel engine (modified for operation using low heating value gas) while the first commercial application of this process for the gasification of RDF is located at Greve in Chianti [Barducci, 1991].

TPS began work on pressurized gasificaiton in the late 1970s and at that time built a 2.5 MWth oxygen-blown bubbling bed gasifier with catalytic tar cracker and ceramic filters (the MINO process). The plant operated for 1,000 hours at pressures up to 28 bar.

In 1989 TPS sold a license for its CFB gasification technology to Ansaldo Aerimpianti SpA for a waste-fueled gasification plant in Greve-in-Chianti, Italy shown in Figure 1. This plant has two 15 MWth CFB gasifiers and a capacity of 200 tons of RDF per day. The gases are burned in a boiler generating 6.7 MWe in a condensing steam turbine. The gas is also used in a neighboring cement factory. The plant has been operating since 1992.

Tars are a major concern in fluidized bed gasifiers and in 1985 TPS started work on the development of a patented process in which the tars are cracked catalytically to simpler compounds at about 900°C in a dolomite-containing CFB.

In 1990 TPS evaluated atmospheric-pressure gasification for application to combined cycle operation for small to medium scale plants and decided to promote commercialization of Biomass

Integrated Gasifier Combined Cycle (BIG-CC) technology. The BIG-CC technology is shown in Fig. 2. and consists of:

- fuel preparation and drying (if required)
- air-blown gasification in an atmospheric-pressure CFB reactor
- tar cracking using a dolomite catalyst in a secondary CFB reactor
- product gas cooling and cleaning in a conventional filter/scrubber unit
- fuel gas compression in a multiple stage compressor
- fuel gas combustion and expansion in a gas turbine generator
- gas turbine exhaust gas heat recovery using a steam turbine generator

Some process data are shown in Table 1.

In 1992 TPS began experimental work and engineering studies for a BIG-CC plant for the United Nations Global Environment Facility gasification project. It is envisaged that a 30 MWe eucalyptus fueled demonstration power plant will be built in Brazil. The gas turbine proposed for this plant is a General Electric LM2500. The TPS system has been chosen for this project.

Gas Characteristics

The product from this process (CFB gasifier/CFB cracker system) is a low heating value gas which can be used as a fuel for duel fuel engines, gas turbines or for gas furnaces/boilers/kilns as shown in Figure 1. An average fuel gas composition from dRDF is shown in Table 2.

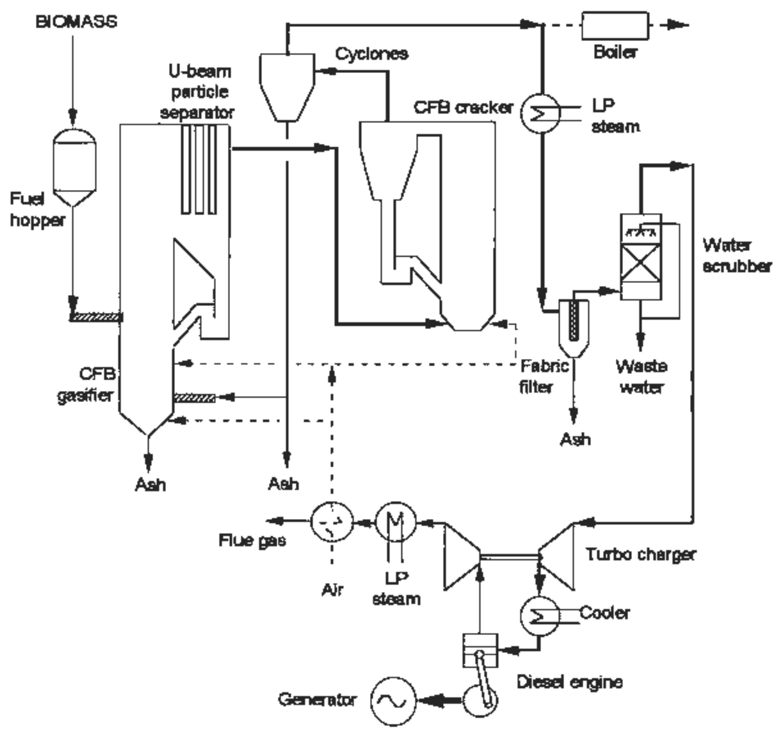

Figure 1 - Flowsheet of Studsvik Atmospheric Gasification Pilot Plant [Annon, 1992]

The gasification of PVC may result in a gas containing HCl, dust and heavy metals. The predicted levels of these contaminants are not reported. The effect of these contaminants on the dolomite bed in the CFB cracker was due to be investigated as of November 1989 [Kaltschmitt, 1996] .

The gas tar content following the cracker and before the venturi scrubber (if in operation) is approximately 1500 g/Nm^3 (gas).

Table 1 - Process Data for TPS CFB Gasifier/CFB Cracker System [Rensfelt, 1991],[Kaltschmitt, 1996]

Process type	Fluidized Bed Gasification
Main feedstock	Woody biomass
Other feedstocks tested	RDF pellets
Main product	Low heating value gas
Main product use	Fueling duel fuel engines, or gas turbines
Primary by-product	none
Feedstock throughput (daf)	360 kg/h
Reactant	Air
Reactor type	Circulating fluidized bed
Primary reactor operating pressure	slightly >1 bar
Primary reactor operating temperature	700-900°C
Secondary reactor type	Circulating fluidized bed
Secondary reactor operating pressure	slightly >1 bar
Secondary reactor operating temperature	850-950°C
Gaseous waste flowrate	none
Liquid waste flowrate	<100 mg/nm3
Solid waste flowrate	proportional to feed ash content kg/kg daf feed

PERFORMANCE

By June 1990, the Studsvik 2MW_{th} gasifier had been operated for a total of 2500 bours of which the CFB gasifier/CFB cracker system bad been operated for 1400 hours and the CFB gasifier/CFB cracker/turbo-diesel engine system for 800 hours [Kaltschmitt, 1996] . The expected diesel engine efficiency (30-32% to electricity) was attained although the exhaust gases contained a higher concentration of carbon monoxide and hydrocarbons than the flue gas from tbe combustion of wood in combustion boilers [Rensfelt, 1991]. The resultant NO_x emissions from the engine are low enough, however, to meet extremely stringent environmental requirements without the need for exhaust gas cleaning [Kaltschmitt, 1996] .

The resultant fuel gas has a beating value between 4 and 7 MJ/Nm^3 and has a hot gas efficiency of approximately 90% [Annon, 1992]. The carbon conversion efficiency is greater than 95% [Kaltschmitt, 1996] . A turn down ratio of approximately 3:1 is reported. It is claimed from the test work carried out that the CFB hot gas clean-up system is an effective catalytic cracker of condensable tars contained in the raw product gas [Kaltschmitt, 1996] . Gas chromatograph results claim to show that downstream of the CFB cracker operating at 880°C, only a few compounds can be detected while upstream of the CFB cracker, significant quantities of tar are detected (Figure 2) [Kaltschmitt, 1996] . Tar conversion efficiencies of 90 to 95% are reported [Kaltschmitt, 1996] .

The product gas has a low tar content. Up to 99% of the tar produced in gasification is catalytically converted to non condensable gaseous components in the CFB cracker [Annon, 1992].

Table 2 - Summary of Gas Characteristics (dRDF Feedstock) [Kaltschmitt, 1996]

Gas	% volume [Woelke, 1992]
Hydrogen	7-9
Carbon monoxide	9-13
Carbon dioxide	12-14
C_xH_y	6-9
Nitrogen	47-52
H_2O	10-14
Other	0.5-1.0
Higher heating value	4-7 MJ/Nm^3

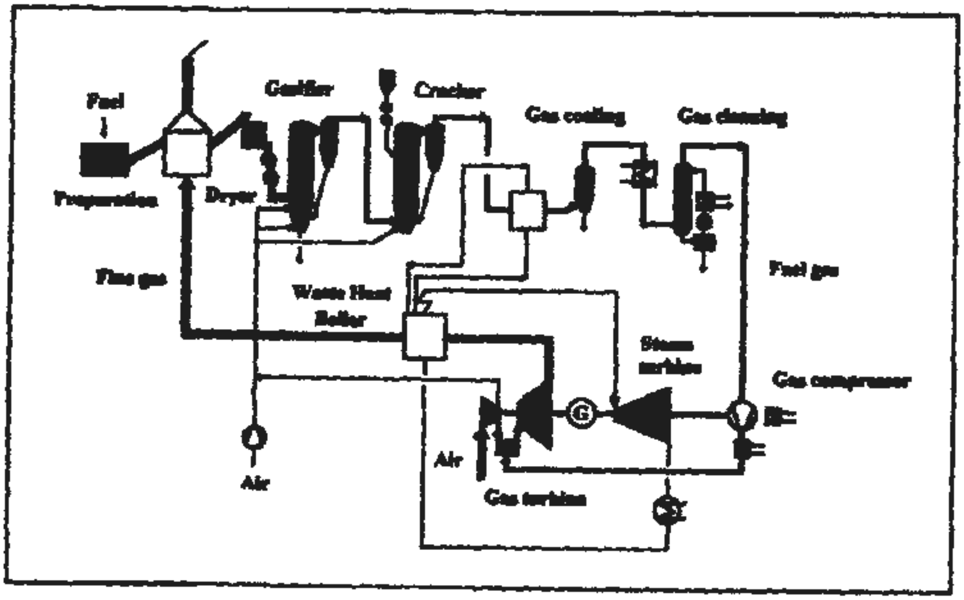

Figure 2 - TPS Biomass Integrated Gasifier Combined Cycle (BIG-CC) process system

GAS EMISSIONS

The gasifier produces no gaseous emissions as the gases produced form the product. When the product gas is used to fuel the diesel engine, it was noted that the hydrocarbon emissions were high and the NO_x and CO emissions were low (see Table 3). Further development is required in this area.

Table 3 - Diesel exhaust analysis

	Before catalyst	After catalyst
Oxygen - %	5	5
CO, ppm	2500	100
Hydrocarbons, ppm	1600	800
NO_x, ppm	50-70	50-70
PAH, mg/Nm^3	0.3	0.15

Note: Catalyst is an oxidation catalyst.

LIQUID EMISSIONS

Liquid emissions in the form of tars are extremely low [Kaltschmitt, 1996] . The tar content from the CFB gasifier/CFB cracker system is less than 100 mg/Nm^3 provided the cracker temperature is above 850°C [Kaltschmitt, 1996] . This low enough for the gas to be used in a turbocharged diesel engine [Kaltschmitt, 1996] .

POLLUTION CONTROL TECHNOLOGIES

Following the gasifier, the product gas passes through a second CFB reactor where any tars in the product gas are cracked at temperatures between 850 and 1000°C.

Solid Emissions

This gasification process will produce ash. The ash flowrate will depend on the ash content of the feed material to the gasifier.

PROCESS COSTS

The smallest gasifier which TPS would consider building was suggested to be 15MW_{th} (feed input). For a 52 MW_{th} gasification plant for the production of 17 MW of process steam, (9 MW of district heating and 16 MW of electricity, to be located in Mariestad, Sweden for Gullspång Kraft AB (the 3rd largest power utility company in Sweden), the total investment cost is estimated to be 300 $x10^6$ SEK, £30 $x10^6$ (May 1992).

CURRENT STATUS AND FUTURE PLANS

In an E-mail update 3/5/99 J. Birse (of the Trade Association to the UK Bioenergy Industry, jim@britishbiogen.co.uk) said "Project ARBRE is indeed running on a TPS updraft gasifier that I believe has been well tested in Sweden. Total power output is around 10 Mwe with some power used on site in fuel processing etc., leaving 8Mwe DNC.

The project is owned by a partnership including TPS and Schal of the Netberlands, but dominated by Yorkshire Environmental.... Until recently ARBRE had problems recruiting farmers to grow SRC but recent sterling work by MAFF officials with the official in Brussels has won equal subsidy treatment for the crop along with an additional establishment grant to cove the initially high establishment (low volume, immature market) costs and to help overcome farmer resistance to a relatively untried crop (in the UK). I believe a couple of hundred hectares have been planted so far and some 500 more will be planted this spring. In total I think they plan to plant 2000Ha. In the startup phase, the plant will run on forestry residues. The plant is now under construction and I think will be commissioned sometime in 2000. For more information check the MAFF webb site, www.maff.gov.uk/farm/acu/acuren-4.htm.

The pilot scale gasification plant at Studsvik is currently operational. The CFB/gasifier/CFB cracker/diesel engine combination is ready for demonstration on a commercial scale [Kaltschmitt, 1996] . Studsvik are currently investigating the production of a suitable fuel for gas turbines from the atmospheric gasifier - discussions are currently underway witb General Electric and others to obtain a suitable 10-20 MW aero derivative gas turbine.

The license for the Studsvik atmospheric CFB gasification system is held by Studsvik. The gasification plant at Greve in Chianti was built under license from Studsvik by Aerimpianti who hold the license for Studsvik combustion plant in Italy.

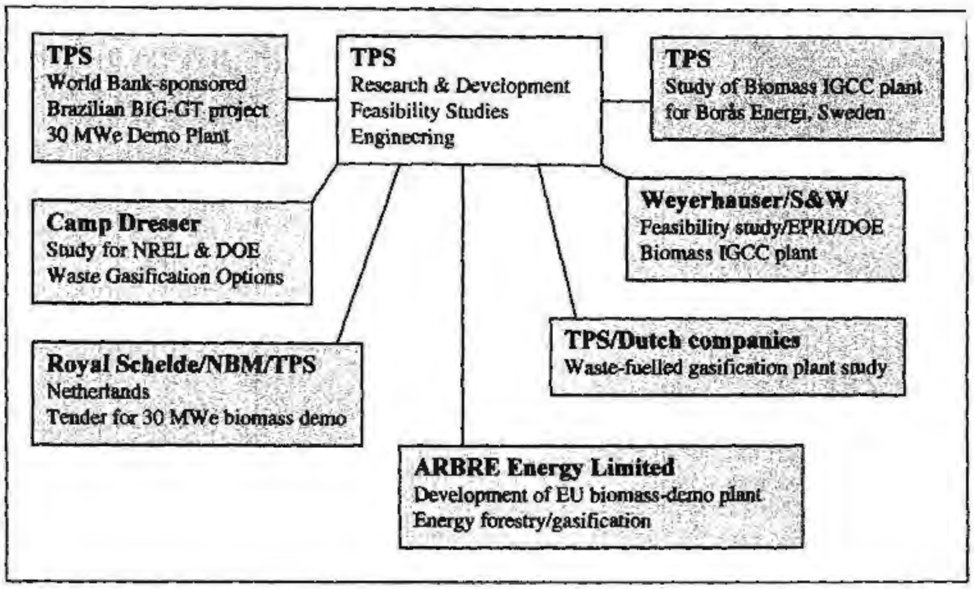

Figure 3 - Current TPS IGCC activities

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3.19 Varnamo IGCC Plant, (Bioflow, Sydkraft, Foster Wheeler)

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Process: First Integrated Gasifier, Combined Cycle , recirculating pressurized fluid bed for biomass to operate

On September 30, 1996 I visited the Varnamo IGCC (integrated gasifier-combined cycle) plant in Varnamo, Sweden with Eric Rensfelt of TPS. The IGCC system has the advantage of high electric efficiency and very low emissions. It is the first plant in the world to achieve IGCC operation. A report was given at the IEA meeting on the operation of this plant [Kaltschmitt, 1996] A joint venture company, Bioflow Ltd., was established in 1992 to enhance the development and marketing of the technology.

The layout of the plant is shown in Fig. 1. and the arrangement is shown in Fig. 2. The fuel is dried to a moisture content of 10-20%. It uses a pressurized fluidized bed recirculating gasifier. Air is compressed and enters the grid of nozzles, fluidizing the solids above the grid. The biomass is pyrolyzed immediately as it enters the fluidized bed. Gas flows upward in the gasifier with the fluidizing solids comprising ash, char, (sand and dolomite) and bed material. The gas and solids enter the cyclone where the major part of the solids are returned to the lower part of the gasifier. The gas leaving the cyclone flows into a gas cooler where it is (cleaned and) cooled and then to (in) a ceramic filter vessel for dust removal. The cleaned gas passes through a governing valve to the gas turbine combustors.

The flue gas from the turbine enters a conventional heat recovery steam generator. The superheated steam drives a steam turbine. The waste steam is used for district heating together with some other rather low temperature cooling water.

First Design (work) studies on the plant began in 1989. Commissioning started in 1993, but was not finished until 1995. The first fully integrated test run was performed in autumn 1995. In 1996 the unit was operated at 100% load with the gas turbine fired from the gas produced in the gasifier in excess of 340 (for 150) hours. The plant has been in operation (gasification mode) for (4500) 3200 hours. The Process data and main suppliers are shown in Table 1. The plant generates 6 MWe (efficiency 32%) and 9 MWth (efficiency 50%) for a total efficiency of 82%. A typical gas composition range is N_2, (44) 45-50%; H_2, (11) 10-12 %; CO, (16) 15.5-17.5 %; hydrocarhons, (6.5) 5-7 %; (H_2O, 12%) and CO_2 (10.5) 14-17 %. All on dry basis. Moisture content in gas 10-14 %. LCV of gas approximately 5-6MJ/Nm^3.

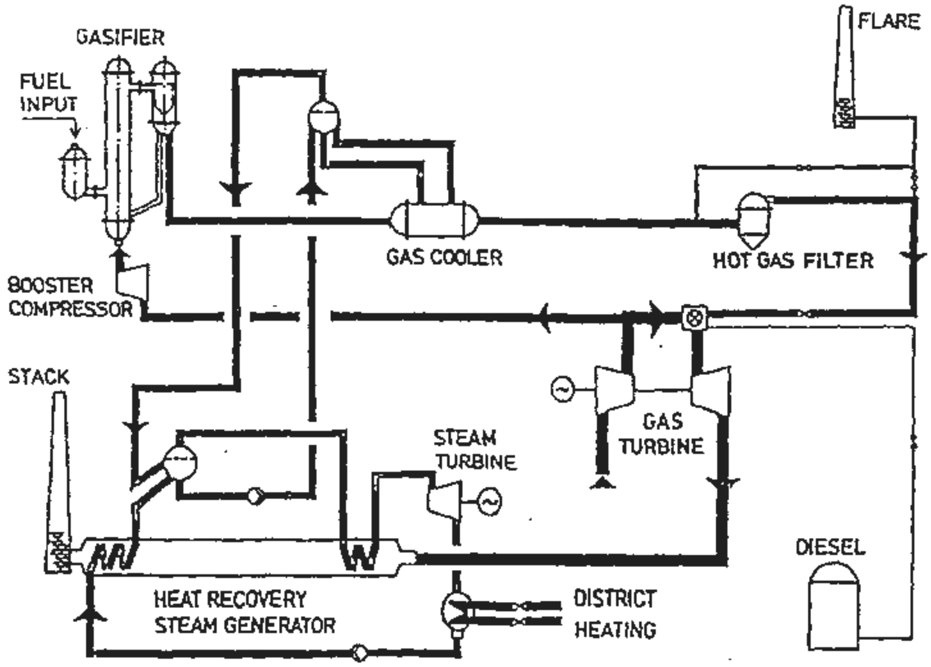

Figure 1. - Layout of IGCC Varnamo plant

It is the first plant in the world to achieve fully integrated operation. This plant will confirm technical and economic viability of the technology and provide engineering data for the design of commercially rated power plants. The next unit is expected to be in the 20-60MWe range.

PROCESS COSTS

The total cost of the cogeneration plant at Värnamo is estimated to be MSEK260, £25million (May 1992) [Anon, 1991]. This cost includes an oversized feed dryer and contingencies.

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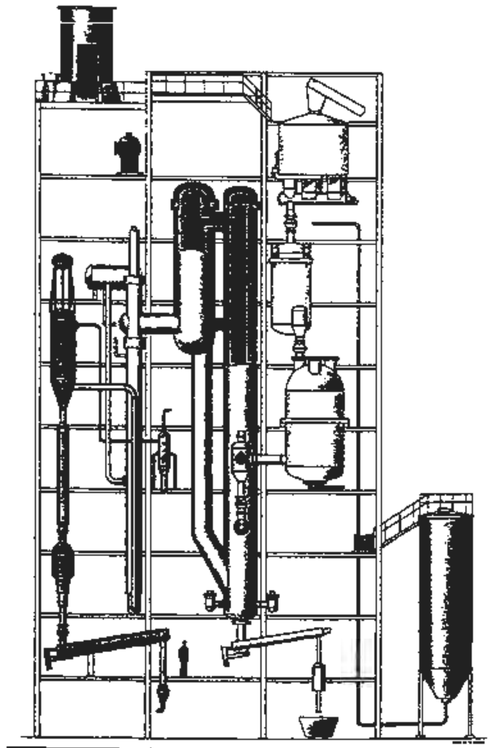

Figure 2 - Arrangement of Varnamo IGCC plant (from report)

Table 1 - Process data and Main Suppliers for Varnamo IGCC plant

Plant Size	18 MW Fuel Input
Fuel	Wood Waste and Chips
Gasification Pressure	22 bar
Gasification Temperature	950-1000°C
Product Gas Heat Value	5 MJ/nm3
Power Production	6MW
District Heating	9MW
Steam Temperature	470°C
Steam Pressure	40 Bar
Plant Owner	Sydkraft
Gasifier	Foster Wheeler Energia Oy
Ceramic Filter	Schumacher
Gas Turbine	European Gas Turbine

Steam Turbine	Nadrowski
Waste Heat Steam Generator	Foster Wheeler Energia Oy
Booster Compressor	Ingersoll-Rand

3.20 Vattenfall Lime Kiln Gasifier (Gotaverken, Kvaerner)

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Fax: 46 8 37 06 82

Process: Circulating Fluidized bed gasifier for lime kiln

On October 14, 1996 I visited the Vattenfall lime kiln gasifier with Eric Rensfelt of TPS. The lime kiln is a necessary part of a large Kraft paper mill. The recirculating fluidized bed gasifier was built in 1990 by Gotaverken Energy Systems and now belongs to Kvaerner. It supplies 600°C gas to operate a 35 MWth lime kiln and also supplies gas for a wood dryer, since the wood fuel averages 58% moisture. An air preheat cools the exit gas from the primary hot cyclone. The gasifier uses dolomite particles for Fluidization. It has operated with 85-90% availability.

3.21 VØLUND R&D CENTRE (Ansaldo) Updraft Gasifier

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Process: Updraft gasifier for straw, wood-chips, heat and power

So far straw firing has taken place at district heating plants and small combined heat and power plants. The combustion technology for this has been grate firing, fluid beds or Vølund's specially developed straw burner the so-called "cigar burner". These technologies can only difficulty be scaled up to utility size without it requiring the use of additional fuel in order to stabilize the combustion process. (From WWW). [Volund, 1997; Krinstensen, 1997].

On the basis of its many years' experience with gasification and pyrolysis of straw, Vølund has started the development of a completely new combustion concept, which is based on known and tested principles, but combined in such a way that if offers completely new possibilities of implementation of straw on a large scale on existing as well as on new plants.

The combustion concept consists of a straw burner with almost the same physical dimensions and outputs as a coal dust burner. It comprises a cylindrical barrel 2 m long, and with an internal diameter of 0.5 m. Compressed straw is pushed into the outer end of the barrel by the action of a screw feeder. The barrel has a total of 600 holes of 10 mm in diameter evenly spaced along its length. These perforations allow hot air at 600·C from the hot air plenum which surrounds the barrel, to enter and to react with the straw. The hot air first dries, and begins to combust/pyrolyse and break up the straw as it passes along the barrel. The bot air supplied to the pyrolysis unit is around 10% of the stoichiometric air requirements for combustion of the straw.

The products of the pyrolysis process are a low calorific value pyrolysis gas in which particles of charred straw are entrained.

The final burning out takes place by supplying secondary and tertiary air in the same way as it is known from the coal dust burners. The output of the burners is approx. 40 MW corresponding to approx. 10 t/h straw being burned in one single burner. The burners can be installed with a distance of 2500 mm which make it applicable in connection with most boiler concepts.

Furthermore, the straw burner makes it possible to burn coal and straw on the same boiler, as the small physical dimensions of the straw burner makes room for further installation of a complete set of coal dust burners on the same boiler. In that connection a feasibility study on a 200 MWel plant has been carried out, showing that with this technology it is possible to achieve utility data which are comparable with coal firing.

Also contact Jørgen Hansen, Head of Mechanical Design Department, Vølund Energy Systems A/S, Falkevej 2, 6705 Esbjerg Ø, Denmark;Phone: 45 75 14 28 44; Fax: +45 75 14 14 02

The aim of this process is the gasification of straw or wood in a 1-1.3 MW_{th} (fuel input) pilot scale updraft gasifier (approximately 200-300 kg/h) for the production of a low heating value gas which can be used as a boiler fuel. Vølund plan to fuel a dual fuel diesel engine with the product gas.

DESCRIPTION

Background

The Vølund gasifier, constructed in 1989, is situated at a power station in Kyngby, Denmark. The gasifier is owned by Elkraft and operated by Vølund and the Danish Technological Institute. Some funding was provided by the Danish government. Approximately 1200 hours operating experience has been gained to date (May 1992) and 100 tons of straw and 40 tons of wood chips have been (separately) gasified.

Process Description

A simplified flow diagram of the Vølund updraft gasification system is shown in Fig. 1 and the gasifier is shown in Fig. 2. Process data is shown in Table 1.

Straw bales from a covered storage area are transferred by a front end loader to a weighing scale. Following weighing, the bales are transferred by the front end loader on to a conveyor feeding the straw bales into a chopping machine. The chopper cuts the straw into approximately 5 cm lengths. The cut straw is transferred to an inclined conveyor by a variable screw feeder. The inclined conveyor transfers the straw to a pelletizing feeder situated near the top of the gasifier. Two hydraulic rams in the pelletizing feeder form the straw into a large cylindrical pellet approximately 50 cm long and 25 cm in diameter (pellet bulk density □ 200-400 kg/m^3). A third hydraulic ram pushes the pellet into the gasifier. As the pellet enters the gasifier, it breaks up into smaller pieces approximately 20 cm long. The pelletizing feeder was only recently installed and was under test at the time of the visit to the plant (May 1992). The maximum feed throughput of the feeder is estimated by Vølund to be 500 kg/h although the feeder has not been tested at this feedrate. The feed level in the gasifier is controlled by a level switch.

The gasifier is a fixed bed updraft gasifier with an outside diameter of 2 m. An in-bed stirrer provides mixing in the pyrolysis zone which is located approximately 5 m from the top of the gasifier. Air to the gasifier is mixed with steam (provided by the neighboring power station) to control the gasifier temperature. Steam is received at 150°C and heats the inlet air to approximately 60°C.

The base of the gasifier is sealed using a water seal. Ash is removed batchwise from the gasifier through the water seal and is stored in a skip prior to removal from site.

The gasifier is operated near atmospheric pressure. A venturi ejector located near the product gas burner extracts the product gas from the gasifier and transports it to the burner. The burner is fitted with an oil fired pilot light which operates at temperatures less than 800°C to ensure efficient product gas burnout.

The product gas flowrate is measured using a pitot tube and an insulated gas probe situated in the gas exit pipe from the gasifier removes gas samples for analysis. The product gas solids and tar contents are measured batchwise using a filter system. The temperatures in the gasifier are measured using thermocouples.

The gasification system is fitted with a venturi scrubber to remove tars and particulates from the product gas. The scrubber system was not in use during the visit (May 1992). The scrubber water is recycled during operation. No analysis of the waste water from the scrubber has been carried out. During operation, the water level in the disentrainment tank is monitored. Water is periodically removed to prevent overflow as a result of condensate accumulation in the disentrainment tank.

Planned Modification, Developments, Extensions

An objective of the Vølund gasification project is to produce a suitable fuel gas to fuel an engine. Updraft gasifiers produce a gas containing a high quantity of tars. Vølund are, therefore, carrying out research into catalytic tar cracking. The work carried out so far indicates that a specific gas composition is required for high tar conversion. Laboratory tests to date on a model gas and model tar have resulted in a claimed tar conversion efficiency greater than 90%. The target conversion efficiency is 99.9%. The tar cracking process has been tested using the product gas and tars from the Vølund gasifier. However, a lower tar conversion efficiency (68%) was obtained.

Vølund plans to install a duel fuel diesel engine to be fueled by a mixture of 2% diesel and 98% low heating value gas.

PRODUCTS

Gas Characteristics

The product of the Vølund gasification process is a low heating value gas which can be used as a boiler/furnace fuel or, after cleaning or upgrading, as a fuel for engines. A representative analysis of the raw product gas from the gasifier is shown in Table 2. It can be seen that a high proportion of the gas is inert.

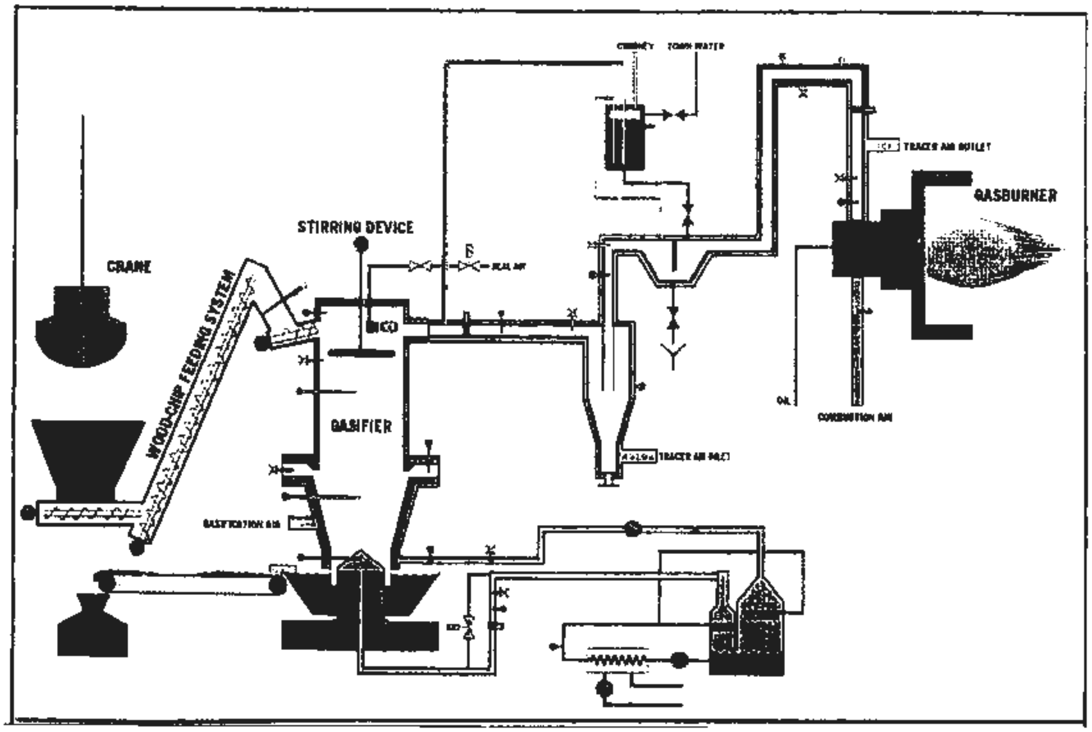

Figure 1 - Flow diagram of the Vølund Harboore Gasifier Plant

The product gas contains a high proportion of tars. It is proposed that future research will crack the tars to produce a gas sufficiently clean for use as an engine fuel. Currently, the product gas could only be used as a boiler fuel.

Liquid Products Characteristics

The raw product gas contains a high proportion of tars. The tars can either be combusted with the product gas in a boiler, removed from the gas by gas cleaning or, as proposed by Vølund, cracked to lighter molecular weight gaseous components.

PERFORMANCE

An energy balance is shown in Table 3. It can be seen that the cold gas efficiency is very low (30%) and the energy currently available in the tars requires recovery if the process is to be used to fuel an engine. Further indication of the excess tars produced is shown by the fate of fuel carbon during the gasification process (Table 4). Under part load operation, the gas tar content has varied from 30-50 g/Nm^3 of gas. This is equivalent to 20-30% of the gas lower heating value. Up to 200 g/Nm^3 of tar has been recorded.

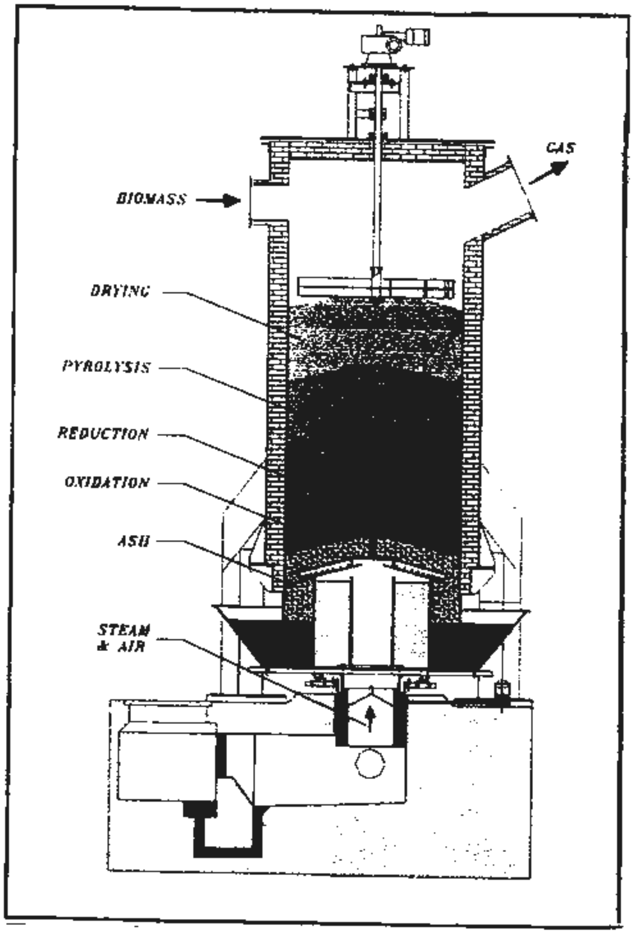

Figure 2 - The Vølund Updraft Gasifier

Table 1 - Existing Process Data - Pilot Plant

Process type	Updraft Gasification	
Main feedstock	Straw, wood	
Main product	Low heating value gas	
Main product yield§	1.81-2.55	kg/kg daf feed
Main product use	Flared at pilot plant	
Feedstock throughput (max)	500	kg/h
Feedstock throughput (max)	1.25	MW_{th}
Primary reactor operating pressure	1	bar
Primary reactor operating temperature	1000	°C
Reactant	Air/steam	
Reactant input rate	0.98-1.86	kg/kg daf feed
Equivalence ratio	20-39	%
Solid waste flowrate	0.05	kg/kg daf feed

§ Assuming the gas density equals the density of air (1.29 kg/m^3)

EMISSIONS

Gas Emissions

The product gas produced by the pilot plant is disposed of by flaring. The flare is fitted with an oil fired pilot flame which operates at temperatures less than 800°C ensuring complete burnout of the product gas. The gaseous emissions from the pilot plant will, therefore, consist of combustion products.

PROCESS COSTS

Capital Costs

The total capital cost of the 1-1.3 MW_{th} (fuel input) pilot plant (including the scrubber system and motors) located in Denmark was DK 4-4.5 million, £0.4-0.45 million (1989). This is equivalent to approximately £800-£900 per tonne of feed.

Liquid Emissions

The gasification system is fitted with a venturi scrubber system. A waste water analysis from the scrubber system has not been performed. The efficiency of the scrubbing system was not available.

Solid Emissions

The gasification system will produce ash (approximately 15 kg/h at a feed rate of 300 kg/h). Approximately 5% of the carbon in the feed exits the gasifier with the ash. Gasifier operation with straw can lead to ash melting due to the low melting point of straw ash (700°C). Ash removed from the gasifier is stored in a skip prior to removal from site.

Table 2 - Summary of Gas Characteristics (Straw Gasification)*

Gas	% volume (dry)
Hydrogen	4.4
Carbon monoxide	11.6
Carbon dioxide	14.7
Methane	4.0
C_2+	-
Oxygen	1.0
Nitrogen	64.3
Gas output rate (dry)	1.40-1.97 Nm^3/h
Gas exit temperature from gasifier	250°C

Heating value	2.6-5.0 MJ/Nm^3
Water condensate in gas	170-240 g/Nm^3
TOC of condensate	6.5-10.0 g/Nm^3

*** Data based on tests with a mean straw flow of 300 kg/h and equivalence ratio of 26%.**

Operating Costs

The current cost of straw in Denmark at the time of the visit (May 1992) was DK 400-450 tonne (£40-45 /tonne).

Product or Production Costs

The product cost was not available.

MARKETS FOR PRODUCT

The product gas from the Vølund gasifier fueled by either wood or straw is currently suitable for use as a boiler fuel. One 4 MW_{th} (fuel input) Vølund updraft gasification plant is proposed for construction for the production of district heat at Harboøre Fjernvarme. Vølund are currently (May 1992) negotiating with the Danish Ministry of Environment for grant aid for this project. Provided grant aid is received, commissioning is planned for late spring 1993.

Table 3 - Energy Balance

	kW	%
Inputs		
Straw	704.0	99.8
Air	1.2	0.2
Total	705.2	100.0
Outputs		
Chemical energy of gas	213.0	30.2
Chemical energy of tar	267.0	37.8
Sensible heat	20.0	2.9
Carbon in ash	109.0	15.4
Heat losses	58.0	8.3
Total	667.0	94.6
Closure, %		94.6
Raw gas efficiency, %		71.0
Hot gas efficiency, %		33.1
Cold gas efficiency, %		30.2

Table 4 - Fuel Carbon

Fuel Input	100	%
Carbon in gas output	22	%
Carbon in tar output	38	%
Carbon in CO_2 output	22	%
Carbon in dust output	13	%
Carbon in ash output	5	%

Further research work is required before tbe product gas from the Vølund gasifier can be made a suitable engine fuel for the production of electricity.

CURRENT STATUS AND FUTURE PLANS

The Vølund pilot plant bas been in operation since 1993 (April 1997) and operated over 12,000 hours, producing more than 90% of all the heat for the city. Work is under way to install a 1.2 MW engine. There is a 4 MW gasifier supplying 600 homes with district heating in Harboore. is currently operational.

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3.22 WELLMAN PROCESS ENGINEERING, LTD.

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Fax: 44 121 601 31230121 555 5651

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Purpose: Updraft Gasifiers with Catalytic Cracker for Power Generation, Demonstration for heat, pilot for power (January, 1999) .

The Wellman Company has been making gasifiers for coal and wood for 75 years. They also manufacture boilers and other industrial thermal equipment. They made hundreds of coal gasifiers that made producer gas for the cities of the world in the period 1923-1950. In the 1990s they concluded that there was a market niche for electrical power generation from wood in the 2.5 to 10 MWe (2.5-10 tons/day, dry basis)range using updraft gasification. In September 1996 I visited briefly with Richard McLellan, Wellman Process Engineer at Wellman in Oldbury, England, and a week later I heard him speak at the IEA conference on large scale gasifiers [Kaltschmitt, 1996]. The gas cleanup system is shown in Fig. I and the gasifier is shown in Fig. 2.

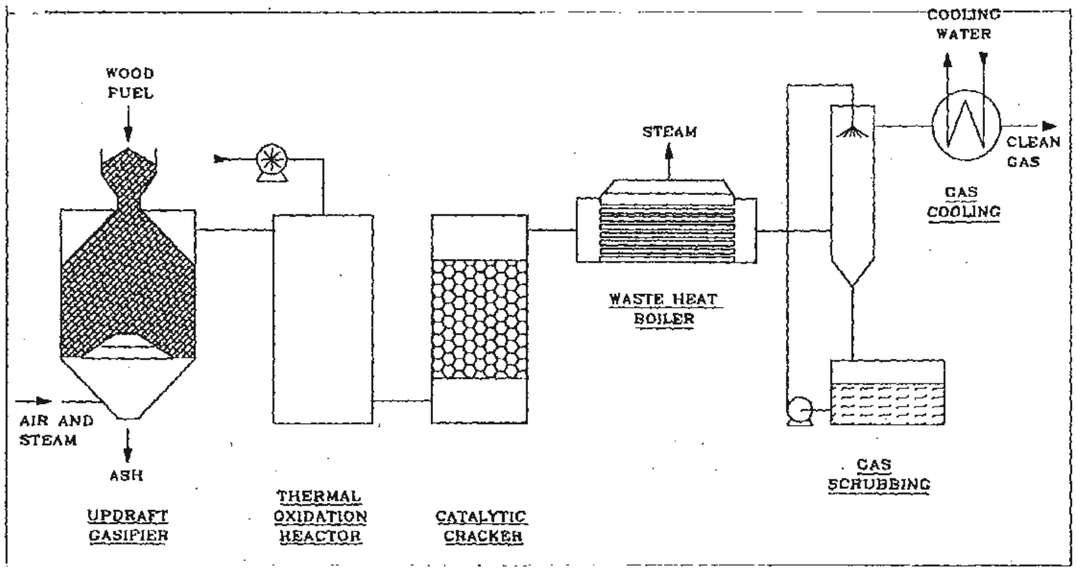

Fig. 1 - Cleanup system for Wellman Updraft gasifier with thermal oxidation and catalytic cracking.

Updraft gasifiers are well suited to applications in which the gas is to be burned in an open flame to raise steam or for other thermal applications. However, the updraft gasifier has many positive aspects including efficient heat recovery, carbon free ash, and a high tolerance for moisture. There has been a prejudice against updraft (*counterflow*) gasifiers for biomass since the 1970s when a number of gasifiers were sold, only to be shut down immediately because of excessive tar production. So I was particularly interested that a responsible company like Wellman would be venturing into Biomass updraft gasification.

A typical raw gas analysis for the new Wellman system is given in Table 1 and shows 5.8% volatiles condensed at -50°C. These volatiles are of course good fuels, provided they don't condense on cold (below ~ 400°C) surfaces. They can also be cracked thermally and catalytically as shown in Table 1. Wellman has been working over the past three years to test an improved gasifier concept on a Caterpillar 6 cylinder G3406 engine. The average moisture of the wood fuel used was 15% (dry basis). The raw gas passes directly into an oxidative thermal cracker which destroys the majority of the condensable organics (except phenols which are then destroyed in a catalytic cracker). schematic of the process for producing clean gas is shown in Fig. 1 .

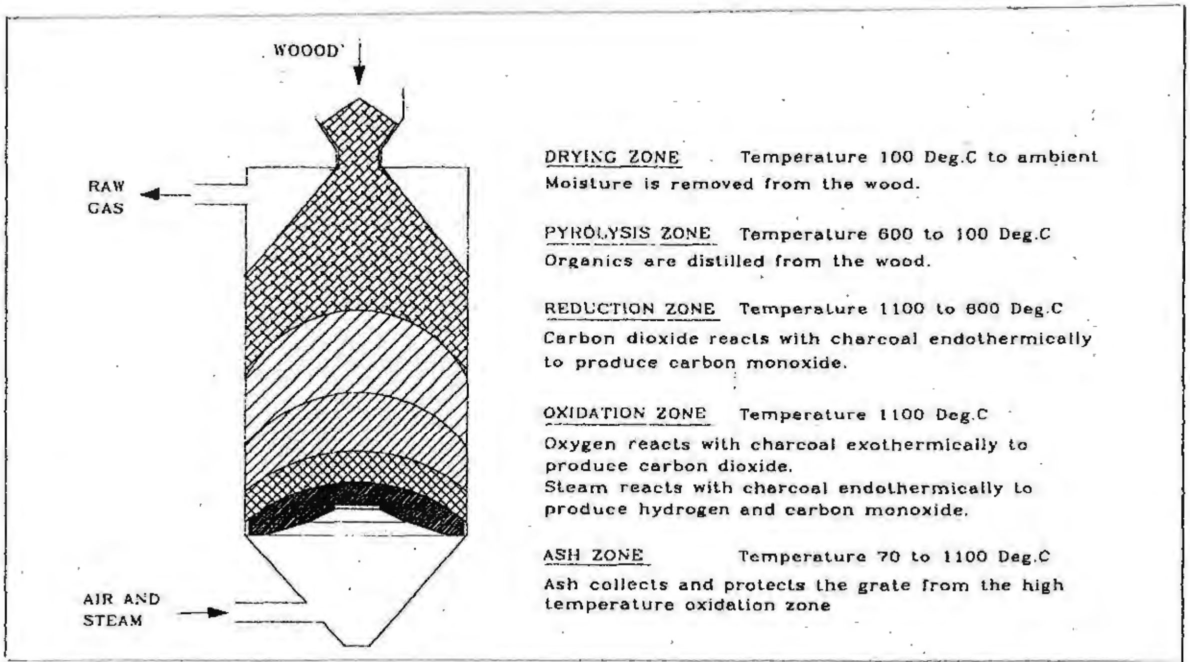

Fig. 2 – Schematic of reaction zones in Wellman Gasifier

Table 1 - Raw gas, thermally cracked gas and thermal/catalyticallly cracked gas from a Wellman updraft gasifier

		RAW GAS	THERMALLY CRACKED	THERMAL/CAT CRACKED
Gas analysis	**Component**	**Vol % (dry Basis**	**Vol % (dry Basis**	**Vol % (dry Basis**
	H_2	6.9	11.8	18
	Hydrocarbons	22.2	2.3	2.2
	CO	29.5	16.5	8.9
	N2	55.3	55.3	58.1
	CO2	6.1	14.1	12.8
Calorific Value	**MJ/Nm3**	5.53	4.55	4.3
Condensable Organics	g/Nm3 (-50°C)	57.5	0.9	0.1

The gas composition after thermal cracking or after thermal and catalytic cracking is given in Table 1. The engine-gas system has been operated over 1200 hours to date and is considered to be "commercial". The clean gas in Table 1 was generated with a wood conversion efficiency of 62%; an additional 20% of the energy is recoverable as steam. An overall wood to electricity conversion efficiency of 25-30% is expected in a commercial system.

There is not yet a consensus on how clean a gas must be to operate engines over long periods or how to measure "tar" concentration. The 1,000 ppm level of condensable organics shown in Table 1 is still rather high, but measurement at -50°C can include many innocuous compounds such as benzene. The ultimate test of gas cleanliness is the time an engine can run between overhauls and 1200 hours is impressive.

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CHAPTER 4 – SMALL GASIFIERS

CONTENTS

Introduction

The world of small gasifiers is in continual ferment, with people, companies and institutions coming and going all the time. It has been difficult to compete with low cost oil, particularly at a small scale. Some gasifiers are developed to a larger scale, some are sold widely - and some quietly disappear. A perfect "snapshot" of all groups today would be out of date tomorrow.

Small gasifiers can be used to supply process or domestic heat quite easily. Production of a gas clean enough to generate power is more difficult, even though over a million gasifiers operated cars, trucks, boats etc. during World War II. In the new future we will also be able to operate micro-turbines, fuel cells and Stirling engines on producer gas.

Small gasifiers will be a key to the healthy development and industrialization of the developing countries (about half the 6 billion world population). The developed countries depend on an infrastructure of phone lines, power lines, water lines and pipelines installed over the last 100 years. Today everyone who wants telephone, power, clean water and gas must move to the city, resulting in megalopolises like Mexico City. Social planners see the benefits of a more evenly distributed population, but neglect the requirement of an expensive infrastructure.

New technology is making it possible to achieve these advantages and the first example is the cellular phone which makes possible communication without phone lines. A small (10-1000 kW) low cost, turnkey gasifier power generation system could make power, water and gas available as well at a small scale. That goal is in sight and the U.S. DOE has instituted a "Small Modular Biomass Power" program to bring it closer. We believe that microprocessor control can cure many of the former ills of small gasifiers.

In this section we introduce a number of manufacturers of small gasifiers. Small gasifiers will also be found in Chapter 5 on Research institutions and in Chapter 2 in our database. There are a lot of companies with a great deal of experience in gasification. Unfortunately, there are a lot of startup companies pretending to more knowledge than they have. Caveat Emptor.

We offer here our apologies to the dozens of other gasifiers not represented here because we did not know of them or because they are quite similar to those given. General references to conference proceedings containing many more details than we present are I General References at the end of this section. Be sure to access our database on the World Wide Web at www.webpan.com/BEF to see new additions.

4.1 AEW, Associated Engineering Works

Contact: Mr. G. M. Satyanarayana

Address: Gamini Compound, Box 17, Tanuku-534 211, A.P. India

Telephone: 91 8819 22950

Fax: 91 8819 24801

Process: Downdraft thermal and power gasifiers

AEW has been in business since 1986 making biomass gasifiers for thermal (0.2-1 GW/hr) and power (20-100 kW) applications. The gasifiers run on wood chips, rice hulls and can be adapted to other fuels. [Satyanarayana, 1997]

Mr. Satyanarayana writes "Our Power gasifiers are fitted with centrifugal tar separators which give perfect filtration. Thermal gasifiers are widely used for bulk cooking. Ric hse gasifiers are designed on a new concept having a tapered grate and constantly rotating ash drum. All the gasifiers are designed and built based on our own in house R & D.

REFERENCES

[Satyanarayana, 1997] Satyanarayana, G. M. , letter and company brochure, 1997.

4.2 Ankur Scientific Energy Technologies

Contact: B. C. Jain

Address: Ankur, near Old Sama Jakat Naka, Baroda 390 008 India

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Fax: 91 48 1042

E-mail: ankur.energy@smn.sprintrpg.ems.vsnl.net.in

Process: Downdraft Gasifiers for Wood and Agricultural residues

I first met B. C. Jain in Indonesia in 1985 where he gave a talk on his small irrigation pump gasifiers. Several hundred of these were installed at that time. (Most of them are no longer working because they can also run on diesel which is handier - and highly subsidized in India).

The FBG series is offered at 1 MJ/hr (100 kW) and 2.5 MJ/hr (250 kW) for fine particle biomass (rice husk, saw-dust, herbal waste and other agri industrial residues. A 100 and a 250 kW gasifier are operating for several years at Fortune Bio-Tech Ltd in Hyderabad. A 100 kW unit operating on rice husk is installed a Win Organics, Raipus. Three gasifiers (1-100 and 2 250 kW) are operating at K N Oil Industries, Mahasamund.

In October 1996 I visited the factory and several installations of Ankur in the company of Professor Parikh (see IITBombay). The factory had many gasifiers on the floor in various stages of completion. There were also a number of gasifiers under test there, including a 7.5, 24, 48, 250 and 500 kW gasifier. They had recently developed a new filtration system that produced "tarless" (at least, no visible mist) gas.

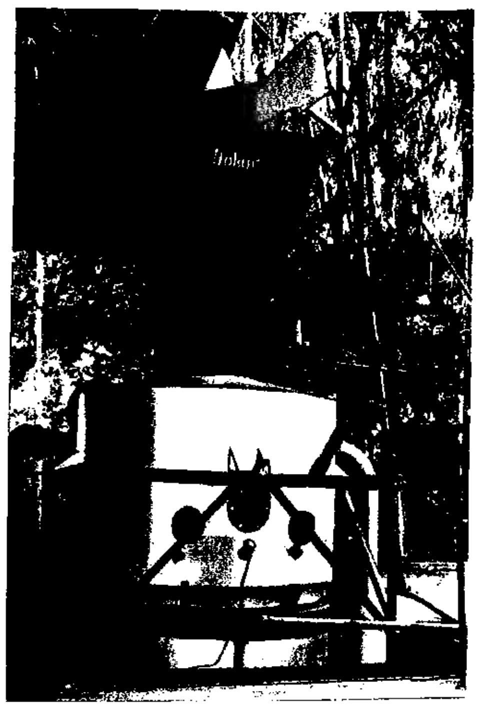

Fig. 1 - 500 kWe Ankur Gasifier

We then visited Mr. B. R. Arora at his factory, Absorbents Chemistry Electronics (ACE) where one of the gasifiers was being used to activate alumina for catalyst manufacture. When first built, the production cost was 8.5 rupees/kg using electricity; he switched to kerosene for heat and the cost dropped to 4 rupees/kg; he then installed the Ankur gasifier and the cost dropped to 2 rupees/kg (about $0.25, $0.12 and $0.06 U.S.). He had been using the gasifier for 6,000 hr and was in the process of expanding to a new one.

Table 1 - Technical Specifications of Ankur AN-500 Gasifier

Nominal Rating - Thermal	5 MJ/hr
Nominal Rating - Power	500 kWe
Gas flow	1,250 Nm^3/hr
Gas HHV	>4.3 MJ/Nm^3
Biomass consumption	500 kg/hr
Feedstock size	<70mmX100mm
Moisture content (WB)	5-20%
Turndown to	40% of rated capacity
Typical Gas	Vol %
CO	19
CO_2	10
N_2	50
H_2	18
Conversion efficiency	75%

We visited another plant making CO_2 by gasifying wood, then burning it to operate a boiler and extracting the CO_2 from the flue gases, regenerating the solvent with steam. I have interesting photographs of these operations.

The Ankur gasifier systems are offered for two different categories of feedstocks. The AG series uses woody biomass (firewood, wood waste, wood from energy plantations, coconut shells, maize cobs, stalks of cotton etc.) and are available for irrigation pumping, various thermal applications and power generation with outputs in the range 60kJ/hr to 5 MJ/hr or 3 kW to 500 kW. They have been used for power generation, irrigation, CO_2 manufacture, Chemical drying (above) and gluten drying. A 48 kW plant has been running at the factory since 1990 and power is fed to the electric grid for $0.04/hr.

Ankur is now offering the AG-500 gasifier for 5 MJ/hr of heat or 500 kW of power with the technical specifications shown in Table 1.

BG Technologies, LLC has been selected as the exclusive marketing agent for the Ankur gasifiers outside of India. A 900,000 Btu/hr coffee drying plant operating on palm nut shells was installed in in February, 1998 and has saved $40,000 as well as making better beans. Contact Wm. E. Partanen, 202 452 1911, 202 452 8323 or Pat Delaaquil, delaqui@ibm.net or see the web page at www. bgtechnologies.com [DeLaquil, 1999].

REFERENCES

[Jain, 1995] Jain, B. C., personal letter, company brochures and articles.

[DeLaquil, 1999] DeLaguil III, P. and Fische, F. S. "Installation, Operation and Economics of a Biomass Gasification System in Indonesia", p. 1087 in [Overend, 1999].

4.3 The Biomass Energy Foundation

Contact: Thomas Reed

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Web Page: www.webpan.com/BEF

Activities: R&D in gasification, biomass book

In 1983, Harry LaFontaine formed the Biomass Energy Foundation, a 501-3-C (Tax Free) Corporation, to work in the field of biomass, particularly gasification. In 1989 Thomas B. Reed joined the BEF as a member of the board of directors. Since then he has published books on energy, biomass and gasification at the BEF PRESS. (See books listed at web page.)

Currently T. B. Reed has developed a wood-gas "turbo stove" (Fig. 1) that burns most biomass efficiently without significant emissions. It uses a 3 Watt blower to develop about 3000 Watts of cooking heat [Reed, 1999].

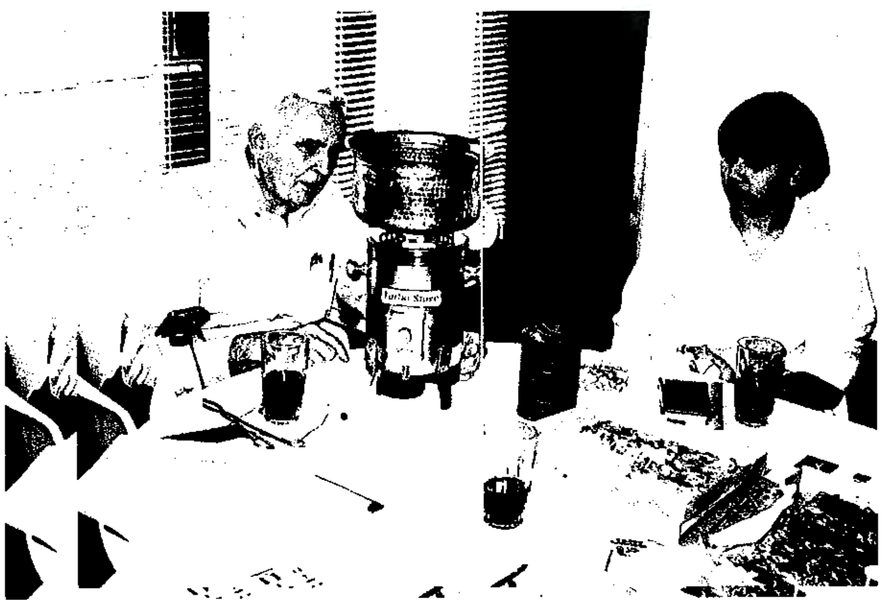

Figure 1 – Turbo stove demonstration in the Philippines

T. B. Reed also works with the Community Power Corporation to develop micro utilities under the DOE/NREL Small Modular Biomass Program. A 12 kW "turnkey" gasifier is currently being developed. (See CPC).

[Reed, 1999] Reed, T. B., "The 'Turbo' Wood-Gas Stove", p. 1093 in [Overend, 1999]

4.4 The Buck Rogers Gasifier

Contact: Bill Ayres

Address: Ag Environmental Products, AEP, Kansas City

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Fax: 913 599 2121

This entry is in the category of interesting history. In October 1981, while working at SERI/NREL, I (TBR) was contacted by Mr. Bill Ayres, representing Buck Rogers of the Olathe Manufacturing Co. in Olathe Kansas. The company manufactured horticultural equipment, chippers trailers, etc. Mr. Ayres asked if I could help them design a gasifier for wood chips. Since I was working for SERI I said I couldn't design it for them, but would be happy to show them our research facility and explain the principles of gasification we were using. They could then adapt them to their needs.

Mr. Ayres, now president of Ag Environmental Products, AEP (1-913 599 6911; 800 599 9209; FX 913 599 2121) was the primary operator and salesperson. Chester (Buck) Rogers was the sponsor and owner of Olathe Manufacturing Co.

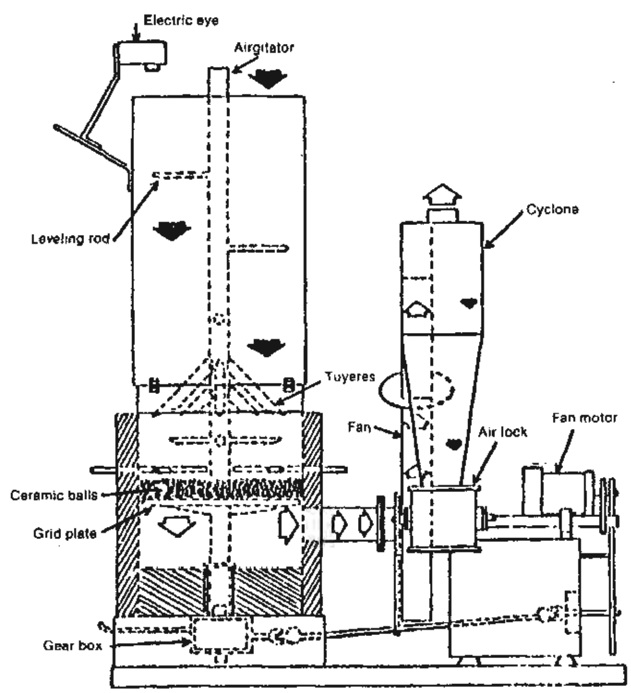

Figure 1. - The Buck Rogers Gasifier

A month later I got a call, asking if I could come see the gasifier they had made. It seemed good to them, but they wanted "expert" opinion. Over the Thanksgiving weekend I visited the factory in Kansas City and saw the workings of their gasifier. It was a stratified, open top downdraft gasifier, similar to the one we were developing at SERI, but it had several improvements [Reed, 1996]. It was of industrial size. The gasifier produced a relatively clean, medium tar (<1,000 ppm) gas. The gasifier was widely marketed and sold in the period 1982-1986.

The gasifier is shown in Fig.1. It uses a very slow rotating rabble arm to distribute a fraction of the air 40-80 cm above the grate. This localizes the start of the flaming pyrolysis zone and prevented it from climbing up and out of the gasifier when using very dry wood. A large blower downstream of the gasifier drew air through the gasifier in the suction mode and delivered it to a burner.

It was designed to retrofit steam boilers at a time when oil was $30-40/bbl. The business was terminated in 1985 when the cost of oil dropped. The gasifier came complete with delivery system and a silo for storage and drying. It was a cylindrical steel vessel 1 m in diameter and 2 m tall.

The gasifier was extensively studied at Kansas State University in a number of excellent theses under Prof. Walt Wallawender. Some of the most accurate data taken for any air gasification has been obtained on this gasifier. Typical values (run 1117) measured for the gasifier are shown in Table 1.

Table 1 - Typical values for operation of the Buck Rogers Gasifier (run 1117) (Nine runs reported in original paper)

INPUT		
Wet Chips	212.0	lb/hr
Dry air	309.3	lb/hr
H_2O	1.6	lb/hr
Total	522.9	lb/hr
OUPUT		
Dry gas	482.1	lb/hr
char	5.5	lb/hr
tar	0.4	lb/hr
H_2O	50.4	lb/hr
Total	538.4	lb/hr
CLOSURE	97.0	%
PERFORMANCE SUMMARY		
Dry Chip Rate	188.1	lb/hr
Chip Moisture (%, WB)	11.26	%, WB
Material Balance Closure	97.0	%
Dry Gas HHV	155	Btu/SCF

Gas Yield	36.9	SCF/lb dry chips
Char yield	2.92	lb/100 lb dry chips
Tar Yield	829	ppm

In normal operation the arm rotated 1-2 times/hr and produced relatively low tar. However, it was found that by rotating the arm faster, more charcoal was extracted at the grate. Under these conditions the heating value of the gas increased substantially, while the amount of tar also increased dramatically. It was concluded that the gasifier could be a useful charcoal producer, when charcoal was valuable, provided tbat the gas was kept hot enough to keep the tar from condensing before combustion.

REFERENCES

[Reed, 1996] Reed, T. B. and Das, A. "Handbook Of Biomass Downdraft Gasifier Engine Systems", 4th Edition, BEF Press, 1996.

[Walawender , 1983] Walawender, W. P., "Technical Evaluation of the Buck Rogers Gasifier" report to Buck Rogers Co., Jan 15, 1983.

4.5 Camp Lejeune Energy from Wood (CLEW)

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Fax: 919 541 7885

EMail: purvis.carol@ epa.gov (jgc@rti.org)

Process: 1 MW power from wood in Downdraft gasifier system

The project demonstrates the technical, economic and environmental feasibility of energy conversion technology. Camp Lejeune supplies wood waste for power plant operation while minimizing transport and maximizing local waste resource utilization [Cleland, 1999] .

PROCESS DESCRIPTION

The plant incorporates a moving bed bulk wood dryer, a downdraft gasifier using hogged wood residues, a gas cleaning and cooling system and a sprk ignition engine as illustrated in Fig. 1. Engine exhaust, mixed with air is pulled through the dryer bed to reduce wood moisture to 8-15%.

The gasifier is 2.1 m in diameter with a 2.4 m deep char bed below the 0.3 m pyrolysis bed. 680 SCM of gas of 6.3 MJ/SCm^3 is produced. Char is removed from the bottom through multiple rotating star valves and a screw auger. The char is burned in a local coal boiler. The gas is cleaned in a cyclone, a heat exchanger, a coalescing liquid separator, impingement filters, a blower, and additional heat exchanger and liquid separator. The Waukesha L7042 GSI turbo-charged engine is rated at 1 MW on natural gas and up to 700 kW on wood.

All components of the system are operational and power is being generated for the Base grid. More than 50 tests have been completed. This may be the longest operating downdraft gasifier-engine generator system operated in the U.S. at this scale. The plant uses only wood from the base landfill and is proving an ideal size for utilization of wood residues at low cost. Prospects for wide-spread commercialization are almost entirely dependent on tar control. All other unit operations have shown good performance and reliability. Unique features include a bulk wood dryer using only engine exhaust heat, designs of impact filters and solids level control, star valve char removal, coalescing separators for liquid recovery and designs for automatic control and synchronization to provide continuous reactor ooperation. Additional funding is being sought to complete modifications to optimize long-term operation.

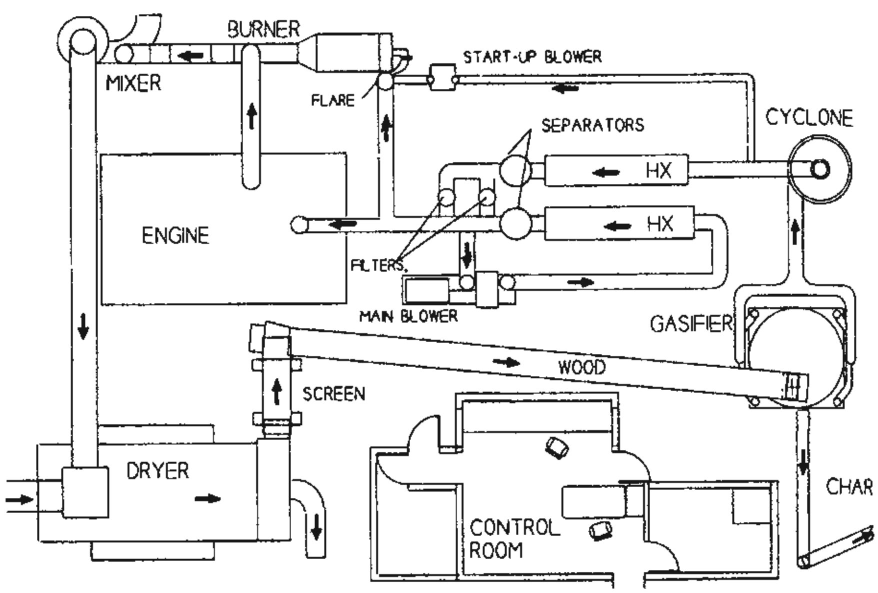

Fig. 1 - Camp Lejeune Energy from Wood flow diagram

The layout of the gasifier plant is shown in Fig. 1.

COSTS

$600-$1200/kWh. Minimum costs can be obtained when gasification system is added to provide alternative fuel to an existing engine generator set.

Darren Schmidt (dschmidt@eerc.und.nodak.edu) was an engineer on this project and is now at EERC in Grand Forks, ND. He says "the reactor was designed for 1100 scfm and was operated mostly at 1000 scfm. ... The project relied heavily on the experience of the gasification supplier, who installed two prior units at this scale and operated them for short periods.

Vernon Harris (vharris001@aol.com) comments "The system is not currently operational, but this is not due to technical difficulties. The project remains under control of RTI and EPA. RTI's interest is in doing a successful research project and not continuously running the facility. Much information will be documented and many things can be learned from this experience. There are not many (if any) projects of this scale (1Mwe) that have run for over 100 hours producing electricity on the grid."

FUTURE PLANS

Future units are planned for demonstration/operationin Bukina Faso, Alaska and other developing countries and mid-size industrial sites in the U.S. Previous experimental units were locataed in Asheboro, NC, Ellicottville, NY and Wakima, WA.

REFERENCES

[Cleland, 1999] Cleland, J. G. and Purvis, C. R., "Camp Lejeune Energy from Wood (CLEW) Project", in [Overend, 1999], P. 1067 (see general references at end of chapter).

[Cleland, 1997] Cleland, J. and Purvis, C., "Demonstration of a 1 MWe Biomass Power Plant at USMC Base Camp Lejeune", in [Overend, 1997] p. 551.

4.6 Chiptec Wood Energy Systems

Contact: Robert J. Bender

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Gasifier: Horizontal, fixed or moving grate, close coupled to supply heat to boilers

On December 2, 1996 I visited the offices and a number of installations of Chiptec Wood Energy Systems in Burlington, Vt. Vermont has over 80% forest cover, so it is not surprising that two major gasification groups are there, Burlington Electric and Chiptec. [NRBM, 1996; Bender, 1996]

Chiptec manufactures an add-on close coupled gasifiers for firing existing boilers. It was founded in 1986, based partly on technology imported from Europe. In 1987 they made a residential gasifier which was adapted to small commercial plants such as Maple Syrup Evaporators. In 1988 they began work on larger automated systems and in 1989 manufactured a 1 MBtu/hr unit. They have developed all the wood chip handling and ancillary control systems necessary for complete installations. They received a patent in 1993 based on their air handling equipment and control techniques and the wedge floor. Chiptec has made over 100 installations in Vermont and surrounding states. The installation at Shelburne Farms was featured on a conference tour at the First Biomass Conference of the Americas held in Burlington, VT in Fall 1993. Installations include schools, hospitals and manufacturing plants. Chiptec markets the gasifiers shown in Table 1.

Efficiency tests were performed on 10 different systems installed between 1991 and 1995, using a Bacharach Combustion analyzer. The results sowed the installed system efficiency ranging from 77.0% to 83.2%.

Table 1 - Gasifiers manufactured by Chiptec

Model No.	Output MBtu/hr [1]	Firing Rate lb/hr	Ash Removal
A-5	0.5	112	Manual
A-9	0.9	201	Manual
C-1	1	223	Automatic
C-2	2	447	Automatic
C-3	3	670	Automatic
CX-4	4	894	Automatic
CX-5	5	1117	Automatic
CX-6	6	1340	Automatic
DX-8	8	1702	Automatic
DX-10	10	2128	Automatic

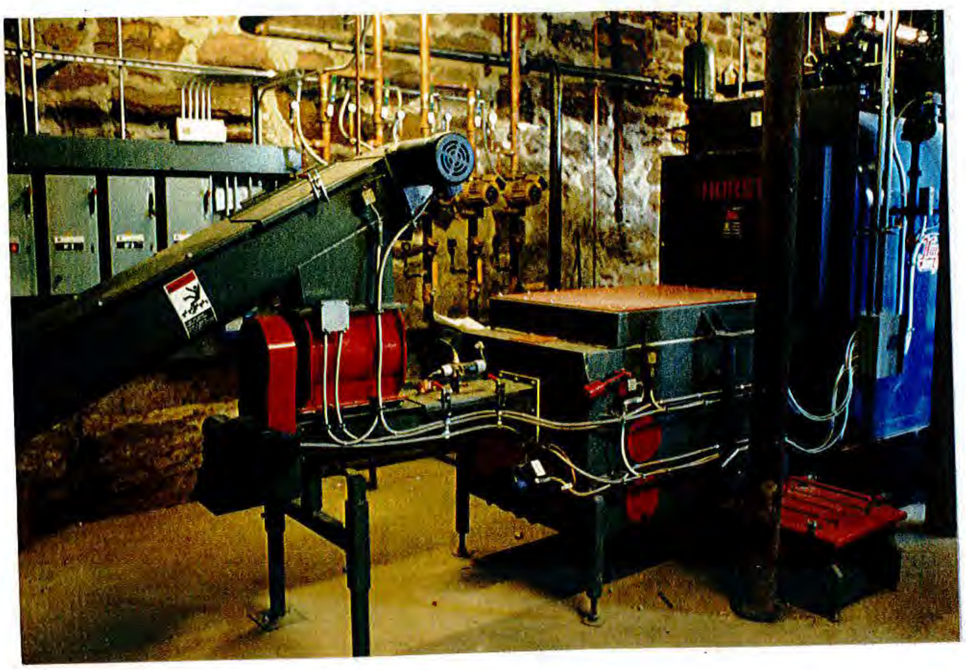

Figure 1 - A Chiptec C-2 gasifier (2M Btu/hr) powering a Hurst SI-50 Boiler

[1] *For 6%-45% MC. The gasifiers all use draft fans. Air locks are installed on all except the first two. The first five gasifiers (to 3,000,000 Btu/hr) have stationary grates, the large ones have moving grates.*

A photograph of the gasifier is shown in Fig. 1. Wood chips are fed automatically into the horizontal gasifier using a "Polyglide" feed system. Air, entering from below pyrolyses the chips and burns the resulting charcoal as the chips move across the grate. The resulting gases pass through a burner nozzle where they are mixed with air, burn and pass to the boiler. The gasifier has a 20:1 turn down ratio which permits it to idle efficiently for reduced loads. The company can supply all the necessary wood storage and handling equipment as well as blowers and controls.

Chips should be in the range 2 ½ X 2 ½ X 5/8 or smaller, with minimum "strings". The gasifier can tolerate up to 45% MC, but excessively wet chips should not be used. Chips should be free of rocks, dirt and other foreign materials. Chip brokers are able to meet these specifications.

A Chiptec A-5 Gasifier and fuel feed system was used to fire an externally heated Sterling engine under an NREL/DOE grant. The demonstration project was successful, showing the symbiosis between gasifiers and Sterling engines.

A private testing firm, Environmental Risk Ltd. (ERL) of Bloomfield, Connecticut, conducted an EPA Protocol Air Quality test on Chiptec equipment at Hazen Union high school under a DOE grant through CONEG. They concluded that the CHIPTEC gasification process has significantly lower particulate emission before any particulate collector is utilized and that the Chiptec combustion process exceeds Vermont State Air Quality Standards with regards to particulate emissions. Tests are also available from other testing laboratories.

The costs of gasifiers are difficult to evaluate since they are so site and equipment specific. However, the Chiptec has installed enough systems to quote a "ballpark" cost of $25,000/Mbtu-hr. There have been a number of economic analyses by their customers before purchase to justify the conversion and after purchase in testimonial letters to CHIPTEC.

A Chiptec A-5 gasifier and fuel feed system was used successfully to fire an externally heated Sterling engine under a NREL/DOE grant.

Chiptec has a Quality Combustion Management (QCM) system which uses Programable Logic Controllers (PLCs) to monitor and control the combustion to maintain load performance and Air Quality. In late 1996, L.S.R., a manufacturer of particulate removal devices, conducted a DOE particulate test on a Chiptec CX-6 gasifier at the boiler flue exit. As is to be expected from gasifiers, the particulate emissions were low and met Vermont standards for particulates without any particulate collector.

REFERENCES

[NRBM, 1996] "Wood-Chip Fired Furnaces Testing Project Air Emissions Testing and Public Health Impacts Analysis", Northeast Regional Biomass Program, 1996.

[Bender, 1996] Letters and company brochures from R. Bender, 1996.

4.7 Community Power Corporation

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Email: Robbcpc@aol.com

Westinghouse had a large international program in the 1990s installing power systems depending on photovoltaic and wind energy. Robb Walt and Art Lilley were two engineers in that division who founded CPC in 1997 to carry on this work after Westinghouse closed the projects down and they.

I (TBR) joined CPC in 1998 to add biomass power to their "micro-utility" business. In 1999 we supplied a 10 kW thermal gasifier to Stirling Technology Corporation to power their 500 Watt Stirling engine under a SMB contract.

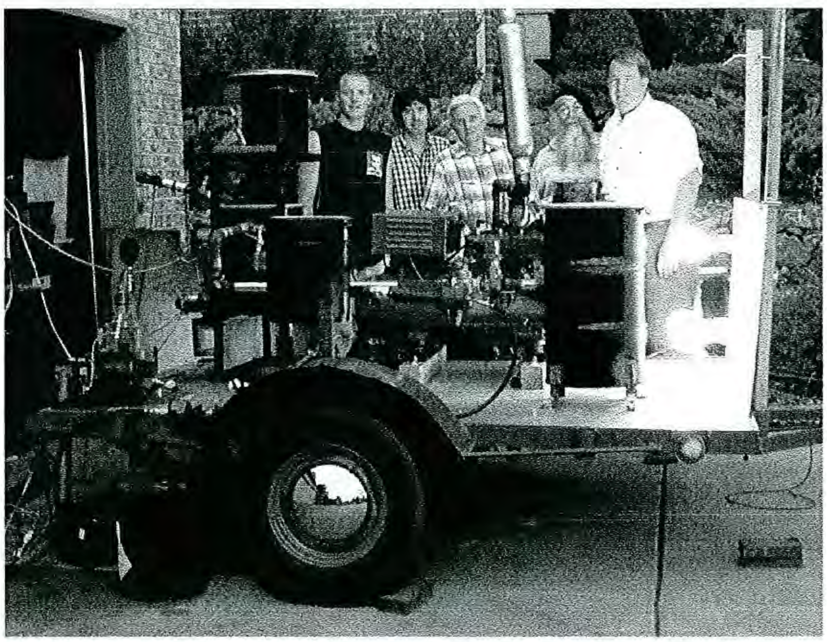

Fig. 1 – 12 kW "turnkey" gasifier system operating 6 500 W bulbs and CPC team (Khris Kircher, Shivayam Ellis, Tom Reed, Agua Das and Robb Walt).

We have measured the tar, charcoal and air/fuel ratio as a function of "superficial velocity" in a special apparatus [Reed, 1999a].

In 1999 CPC was awarded a Small Modular Biomass (SMB) Power contract from NREL to develop a small gasifier utility. CPC built a prototype gasifier (Fig. 1) in the Summer of 1999 and demonstrated it to NREL and Shell International Renewables (SIR) personnel. They were awarded a Phase II SMB contract to build a "turnkey" micro-utility at a coconut mill in the Philippines as a demonstration of the feasibility of small power generation from biomass.

References

[Reed, 1999a] Reed, T. B., "Superficial Velocity – the Key to Downdraft Gasification", in [Overend, 1999]

4.8 Cratech

Contact: Joe D. Craig

Address: Box 70, Tahoka, TX 79373

Telephone: 806 327 5220

Fax: 806 327 5570

E-mail: cratech@ onramp.net

Process: A Small-Scale Biomass Fueled Integrated Gasifier Gas Turbine Power Plant

The big prize for biomass gasification would be the commercial operation of "Integrated Gasifier, Combined Cycle" (IGCC) power plants with expected efficiencies of >40% (compared to current plants <30%). Another big prize is the ability to gasify agricultural wastes, since direct combustion produces intolerable amounts of alkali for heat transfer surfaces. A third prize is hot gas filtration to make gas acceptable for turbine, boiler and genset operation. Cratech has made major steps along these routes in the past few years.

I visited the Cratech plant Dec. 12, 1997 while on a trip to Dallas and Boston. Tahoka is in the heart of the cotton country of West Texas, about 50 miles South of Lubbock. Joe picked me up in Lubbock and, after a Texas breakfast, we drove through the cotton country to "Grasslands", the local area where his plant operates. His family is in the cotton business and I got a very interesting tour of "king cotton" from field to gin, as well as his gasifier. And dotting the landscape, there are very large mounds of cotton trash (sticks, hulls, ...) remaining from the ginning process ripe to be gasified.

Joe Craig has been interested in gasification since the late 1970s when he studied engineering at Texas A&M and built a fluidized bed for sewage sludge. He has been carrying the fluidized bed gasification flag for a long time because:

- A very uniform, controlled temperature can be maintained throughout the reactor, significant when feeding fuels high in alkalis (cotton trash contains 6-8% alkali ash)
- The reactants can be metered into the reactor independently, continuously under microprocessor control
- There are high heat transfer rates from fluid bed particles to injected materials
- The bed acts as a thermal flywheel with vigorous mixing and agitation
- The reactor will accept feedstock particle sizes ranging anywhere from about 2cmX2cmX.5 cm to dust size with any particle size distribution

- FBs are well suited for operation under pressure

There is a need by a very large worldwide market for small size (1 to 20 MWe) power systems that produce environmentally benign and economical power from waste agricultural biomass. Unfortunately, ag wastes typically have 5-20% ash and will quickly foul a boiler or turbine.

Cratech received a contract from the Western Regional Biomass Program (WRBEP) to develop a "Small-Scale Biomass Fueled Integrated Gasifier Gas Turbine Power Plant" [Craig, 1996]. The planned development route is:

- Phase 1: Construct and demonstrate a bubbling FB gasifier of 0.5 tph at 2 atmospheres, including a novel slipstream flow hot gas cleanup system.
- Phase 2: Construct and demonstrate a 1 tph gasifier at 10 atmospheres, including full flow hot gas cleanup
- Phase 3: Integrate the phase 2 system with a 1 MWe turbine

Phase 1 has been completed successfully. In phase I they built and operated a pressurized fluidized bed test gasifier, including the bulk feeding system, the pressurization system, the reactor, a hot gas cleanup (cyclone and filer) and the microprocessor control system. The reactor diameter is 600 mm.

A block diagram of the process is shown in Fig. 1. The system was built and operated for several 8 hour runs and a final 24 hour run with voluntary shutdown.

During my visit I saw the various components needed for Phase 2 being assembled. It is expected that shakedown will occur within the next month or two.

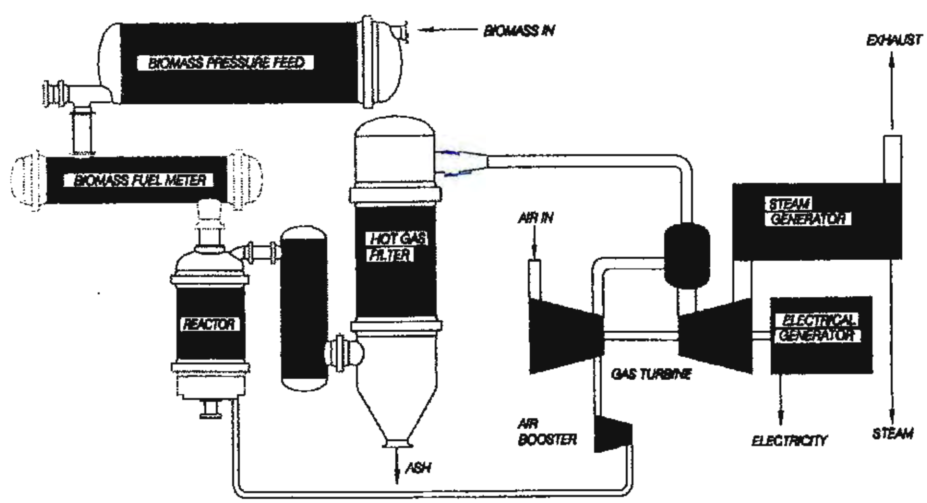

Figure 1 – Block Diagram of Cratech Process

ECONOMICS:

It is generally assumed that the minimum commercial size for IGCC plants is 10-20 MW. However, as part of the Phase 1 study an extensive economic assessment of small scale IGCC operation was made. A 1 MW simple cycle plant, based on existing turbine technology is projected to cost $1.8M, or $1790/kWe. Using turbine technology expected to be available in 2,000, a 1.58 MW plant is projected to cost $2.4M, or $1530/kWe. Larger plants to 10 MWe are also projected [Craig, 1996].

Using conservative assumptions about a 1 MW plant, Cratech says that "if you will accept the assumptions given (for a type A power plant) and you agree that a 20% after tax rate of return is acceptable, then selling your electricity for $0.06/kWh and steam for $4.00 per mt, the answer is yes because the IRR is over 20%."

We will watch these developments with interest.

SPONSORS: The work has been supported by WRBEP, NREL, and the EPA.

REFERENCES

[Craig, 1996] Craig, J. D., "Development of a Small-Scale Biomass Fueled Integrated Gasifier Gas Turbine Power Plant: Phase I", Final report, Grant DE-FGg65-91 WA08318, the Western Regional Biomass Energy Program, (Lincoln, NE) Sept. 24, 1996.

[Craig, 1997] Cratech information sheet 8/6/97.

4.9 Fluidyne (Australia)

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Fax: 09 838 6132

Downdraft Power Gasifiers

Doug Williams has been a loyal contributor to the GASIFICATION section at CREST. Late last year he announced that Fluidyne was closing operations – at least for now. Meanwhile, as this book goes to press, I am waiting to hear from Jack Humphries. p-h-energy@ clear.net.nz, the original developer of Fluidyne. He is getting back into gasification.

Fluidyne has been working in the development of wood gasification for engine powered electrical generation since 1977. Since the 1984 introduction of the Pacific Class model (winner of the 1984 New Zealand Steel Awards) fourteen of these 35 kWe wood gasifiers have been installed around the world. The proven high performance gas making process of Fluidyne's technology removes the problems of condensable tars forming in the system. This enables simplified gas cleaning without any polluting waste streams. The Fluidyne gasifier was selected for the renewable Energy Training Center in Furstenwalde, Germany and for the willow coppice fuel trials at Bristol University in England. The layout of a typical (50 kW) gasifier system is shown in Figure 1 [Fluidyne, ND].

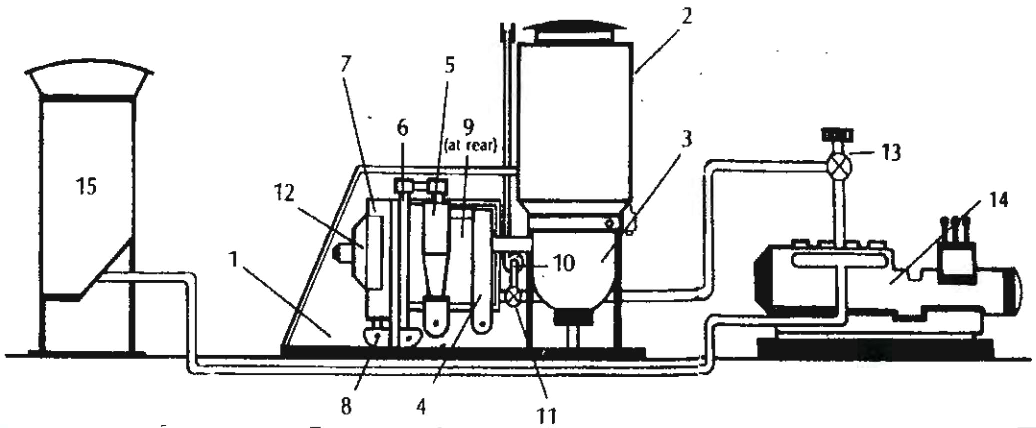

Fig. 1 - Layout of typical Fluidyne gasifier plant showing (1) Supporting frame, (2) Wood fuel container, (3) Hearth, (4) expansion chamber (coarse particles), (5) Multi Cyclone, (6) saturating cooler, (7) condensing cooler, (8) condensate tank, (9) volume filter, (10) start-up fan, (11) change-over valve, (12) gas cooler fan, 13 engine gas/air mixer controller, (14) engine/generator set, (15) wood drier using waste heat.

Fluidyne has a great deal of practical experience relating to fuels for engine applications and the interfacing of the gas with engines. To meet the governing standard for power generation with diesel engines (DBS5514/649, Class A2) Fluidyne manufactures a bolt-on dual fuel gas conversion kit designed for each engine. The kit does not restrict the engine in any way from returning to 100% diesel operation and has been installed on Lister, Caterpillar and Isuzi engines.

A consultancy and supervisory service is also available to projects lacking in the practical expertise of operation and problem resolution associated with biomass gasification.

REFERENCES

[Fluidyne, ND] Fluidyne, company brochures, letters from Humphreys and Williams, Emails at Gasification@CREST.org

4.10 HTV Energy

Contact: P. Juch

Address: HTV Energy, Mittelgaustrasse 205, CH-44617 Gunzgen, Switzerland

Telephone 41 62 216 58 44

Fax: 41 62 216 51 09

In October 1996 I visited HTV and saw their gasifier-engine installation in operation. The downdraft gasifier operates a 750 kW engine generator set and is shown schematically in Fig. 1.

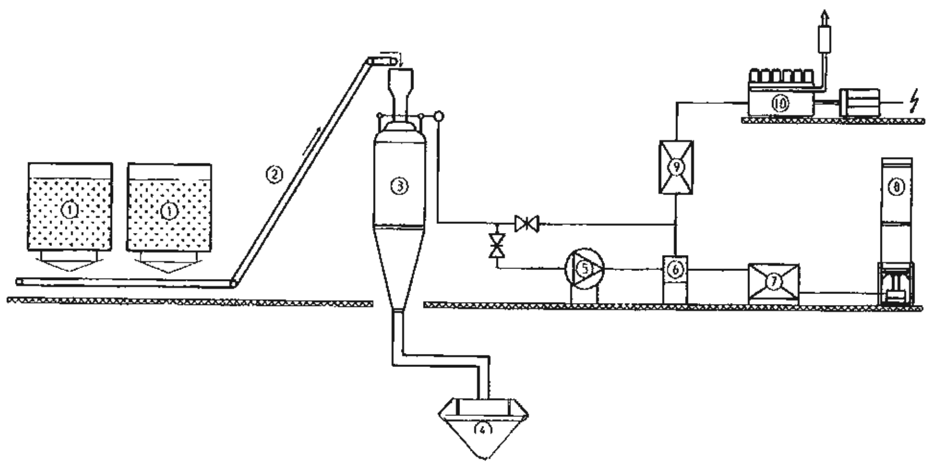

Fig. 1. Schematic of HTV gasification plant showing (1) Fuel container, (2) Fuel feed, (3) Juch-Gasifier, (4) char-ash container, (5) flare fan, (6) condensate reservoie, (7) gas cooler, (8) Gas flare, (9) gas cleaning, (10) motor generator.

The development was started by Mr. Helmut Juch in 1985. In 1991-92 he demonstrated that their system can produce wood-gas that can be used in engines without the usual tar and phenol problems. The gasifier has now been operated 3500 hours and the engine about 250 hours at the Kestenholz plant. The demonstrations in Kestenholz gave a gas with 5 - 6.5 MJ/Nm^3 with an efficiency of 75-95%. The exhaust gas from the engine is under the German limits for incineration. The ash from the gasifier is acceptable in landfills. The layout of the plant is shown in Fig. 1 [Juch, 1997].

A contract has been signed to build a commercial plant near Leipzig called the "Energiezentrum Espenhain".

REFERENCES

[Juch, 1997] Juch, P., personal letter and company information and brochures

4.11 HURST BOILER & WELDING, INC.

Contact: Gene Zebley

Phone: 912 346 3545

Fax: 912 346 3874

E-mail: hboiler@rose.net

Process: Underfeed stoker, travelling grate close coupled gasification

Hurst Boiler and Welding Co, was established in 1967. Hurst has successfully engineered more systems utilizing a wider variety of fuels than any other firm in the world [Zebley, 1998]. The gasifier can be described as a "close coupled" gasifier in which gasification is followed immediately by combustion at the boiler to raise steam.

Fuels include 50% or less wood (chips, bark, sawdust, shavings, sander dust), MDF, tires, paper, cardboard, sludge and hulls. Installations range from 1.7-66 M Btu/hr. Over 400 systems have been installed.

Hurst provides engineering, fabrication and manufacturing, installation and operator training all "in house". Hurst has 200+ employees to provide custom installations.

Zebley says :we currently market our gasification system in conjunction with our boiler systems. In the past two years we've begun installing STAG (stand alone gasification) units to retrofit steam generating systems which were installed with inadequate combustion systems capable of only producing a fraction of the necessary heat output. This system has huge potential for similar retrofits all over the world."

REFERENCES

[Zebley, 1998] Letter and information by Email, 1998

4.12 Shawton Engineering

Contact: Dr. Donald C. Patrick

Address: Junction Lane, Sankey Valley Industrial Estate, Newton le Willows, WA 12 Bon, England

Telephone: 44 1925 220 338

Fax: 44 1925 220 135

Process: Downdraft power gasification

The following report of a site visit was posted on the Email in August 1997 by Dr.David Beedie of the School of Engineering, the University of Cardiff in Wales (beedied@cf.ac.uk) [Beedie, 1997].

"I recently reported to this list for Dr. Donald C. Patrick that he offers biomass gasification systems for small scale power, heat only and cogeneration of heat and power, CHP applications. At Dr. Patrick's invitation I recently visited his gasifier-engine installation in NW England, and I am reporting on the visit to the list. Dr.Patrick showed myself and three associates, Andrew Heggie, Simon Levy and Marc Howell, around the unit. The following information is a combination of what we saw and what Dr. Patrick told us.

The gasifier is a downdraught unit sized for a ton of biomass per 3 hours. Feeding is currently manual, into an airlock-hopper above the reactor vessel. Fuel is dropped into the reactor by releasing the hinged gate forming the bottom of the hopper. Optimum fuel moisture content is around 25% wet basis. The reactor process details are secret but Dr.Patrick claims that his gasifier achieves good tar elimination by attaining very high temperatures ('1600°C') inside the reactor, although the gas exits the reactor at 380C. En route to the engine the gas passes through cyclones, bag filters, water scrubber, mist eliminator & fan-cooled condensate remover. I can report that it appears to be a solidly engineered system.

The engine is a naturally aspirated Perkins 6-cylinder diesel engine which has been modified for producer gas by conversion to spark-ignition along with piston & combustion chamber alterations, with some de-rating to 150kW output. After starting the system the gas is flared for 30 minutes then the gas is diverted to the engine. The output of 150kWe is sustained at a fuelling rate of 3 ton/10hours. Assuming 15 MJ/wet-kg, the input rate is 1.25 MW gross and the overall efficiency of electrical power production is 12%. In a CHP application much of the remainder would be recoverable as heated air from the engine's fan-cooled radiator and/or hot water from the cooling jacket and exhaust gas heat exchanger.

Dr.Patrick reports the gasifier operates well on a variety of solid biomass wastes of typical dimensions from 2cm to 10cm. Materials he has tested include various industrial and agricultural wood wastes and various densified briquetted materials including animal process residues.

He offers a testing service, providing laboratory analyses of gas, ash & condensate from an independent accredited laboratory. The system we saw is about to be shipped to India to act as a demonstration plant and Dr.Patrick is engaged in building further systems for different outputs of 40kWe and 500kWe."

REFERENCES

[D. Beedie, 1997] D. Beedie Email reporting site visit

4.13 System Johansson Gas Producers

Contact: SJG, System Johansson Gasproducers,

Address: PO Box 295, Halfway House 1685; Midrand, South Africa.

Telephone: 27 11 310 1008;

Fax: 27 11 805 1138

Process: Patented tarfree downdraft power gasification

In 1985 I visited the Johansson gasifier development site, midway between Johanesberg and Praetoria, South Africa. Mr. Johansson is an engineer who has had a long time interest in gasifiers. At that time Mr. Johansson was operating a sawmill on a 30 kWe downdraft gasifier of his own construction. The original system is still in operation and has supplied power to a sawmill and for domestic use for over 10,500 hours service, and is still being used today.

The patented SJG gasifier uses a high temperature cast refractory hearth, with reinforced refractory insulation also of the outer containment up to the gas outlet and primary air preheating distribution ring. The gasifier works most efficiently with gas engines, such as the Caterpillar, Jenbacher SITA or SINA gas engine generating sets. However, it also works at lower efficiency with converted petrol engines or with TA or NA aspirated diesel engines with pilot diesel fuel.

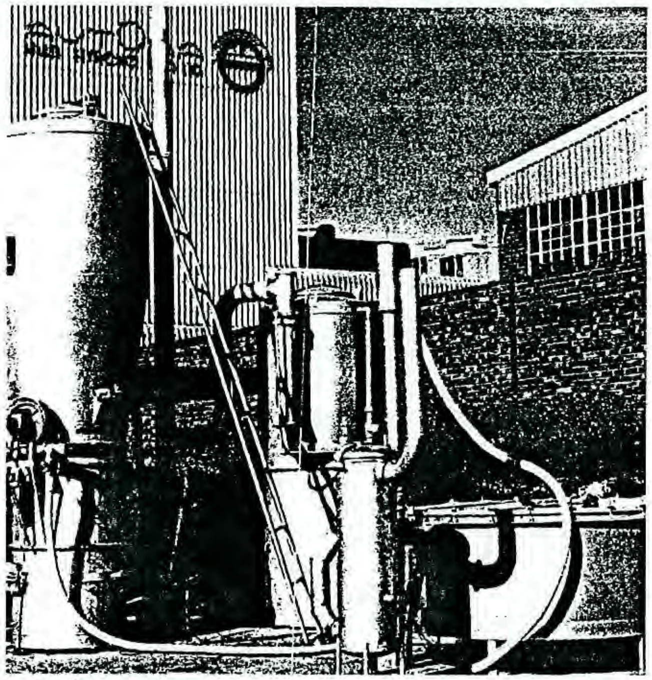

Fig. 1 – 100 kWe SJG gas producer undergoing performance tests at the manufacturer's workshops in Sevenza, Edevale, Transvaal

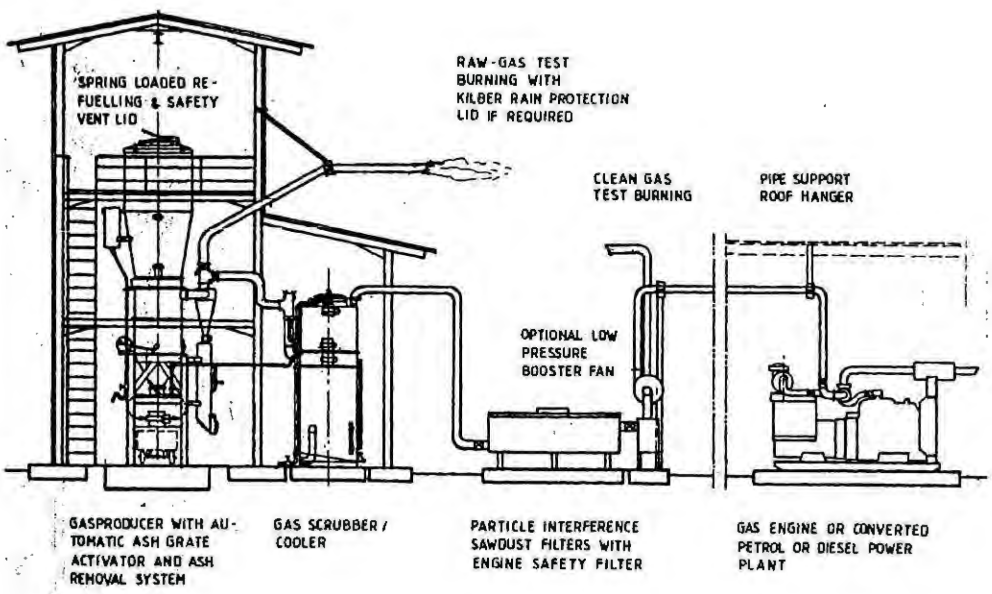

Fig. 2 – General arrangement of SJG gasifier for engine applications

The South African CSIR laboratories measured the composition of the gas as: CO_2, 9.8-10.7%; CO, 22.2-24.3%; H_2, 22.3-22.5%; CH_4, 1.9-2.1%; N_2 42.9-41.5 vol %; Gross heating value 5.9-6.2

kJ/Nm^3. (This is quite high for downdraft gas.) The methane number when calculated on the Caterpillar computer program was for test 40 = 56.8 and for test 41 = 55.9. CRE also made tar tests but could not find any traces of tar with their measuring equipment.

The gas is cleaned with a hot coarse dust cyclone, followed by a cooler-scrubber and a particle interference sieved sawdust filter and finally passed through a 5 micron Donaldson engineering gas safety filter. When ideal hard sieved particle interference filter media is used the main filter media is changed typically every 1,000 hours. The gas is "tar free" (tar below detection limits at CRE). An optional low pressure booster fan brings the engine output to almost full power.

The gasifiers are offered in five standard sizes from 50 kWe (120 Nm^3/h) up to 375 kWe (850 Nm^3/h) max power when powering SITA gas engines (or up to 250 kWe with converted petrol engines), but larger or smaller gas producers can also be supplied. The gasifiers can also be offered with semi-automation. Mr. Johansson has had extensive experience with a wide variety of fuels.

Table 1 - System Johansson gasifier installations

Year Built	Customer	Output Nm^3/h
1983	K.G.J. prototype gas producer in RSA	120
1983	Leubank/Zoekop Farms	80
1990	Badenhorst/Shingwedsi in RSE	450
1990	DeVries Carolina Farm in RSA	120
1990	Department of Agriculture (mini wood gasifier	8
1993	Power Gas50ifiers International, UK	450
1995	Reynolds/Ind40ia Project	450
1995	Industrial Devel25opment Corporation	40
1996	KGJ Modifier General Purpose Hearth for high density sawdust briquettes and wood	25

Gus Johansson is a responsible engineer in South Africa, the "manufacturing power house" for the African continent.

Technical inquiries should be addressed to: System Johansson Gasproducers, PO Box 295, Halfway House 1685; Midrand, South Africa. (Tel: 27 11 310 1008; Fax: 27 11 805 1138)

Commercial enquiries should be forwarded to: Carbo Consulting and Engineering (Pty) Ltd; Box 1397 Cramerview; Bryanston 2060, South Africa. (Tel:27 11 886 6727; Fax:27 11 886 6721)

REFERENCES

[Johansson, 1999] Email report to T. Reed, Sept. 1999
[SJG, 1997] "System Johansson Gasproducers", 28 page technical company brochure

4.14 Thermogenics

Contact: Stephen C. Brand, VP, General Manager

Address: 3620 Wyoming Blvd., NE, Suite 210, Albuquerque, NM 87111

Telephone: 505 298 4381

Fax: 505 293 5150

Email: thermogenics@worldnet.att.net

Web Page: www.thermogenics.com

Process: Novel Inverted Downdraft Gasifier

Thermogenics was founded in the mid-1980s by Tom Taylor, president of Gentronix, a family agricultural business. He invented a new type of co-flow gasifier with fuel and air fed from the bottom. On the basis of early work in Cuba, NM (which I visited in 1986) he incorporated the Thermogenics company in 1990 with Mr. Steve Brand as manager. I visited the pilot plant in May 1986. I again visited the new plant in January, 1999, and inspected the new gasifier intended eventually for making synthesis gas.

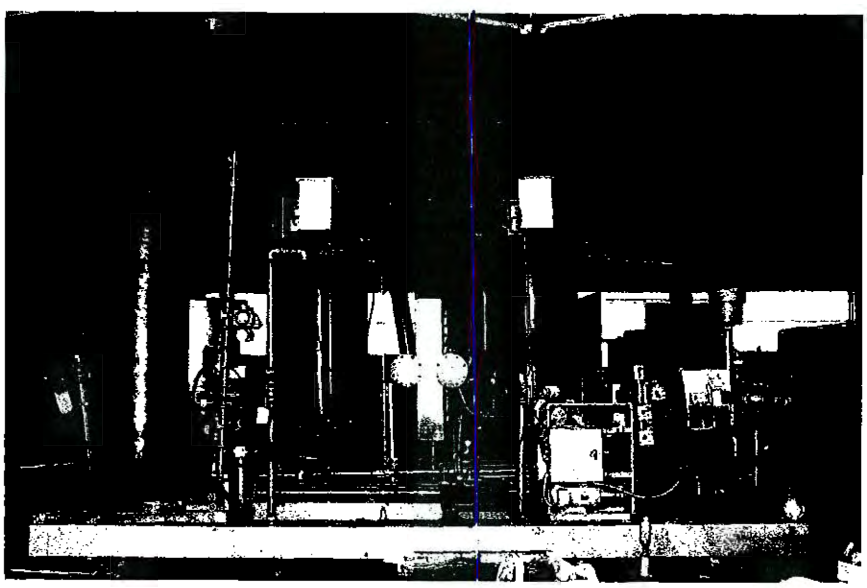

Fig. 1 – Synthesis gas plant showing gasifier at left, mechanical gas cleaners and ESP center, January 1999

The gasifier is fed by a pressure compensated blower through internal sparge pipes. Because the fuel and air flow up, there is no grate, and rocks are removed from the bottom section. The gasifier is shown in Fig. 1. A flow sheet for the system is shown in Fig. 2.

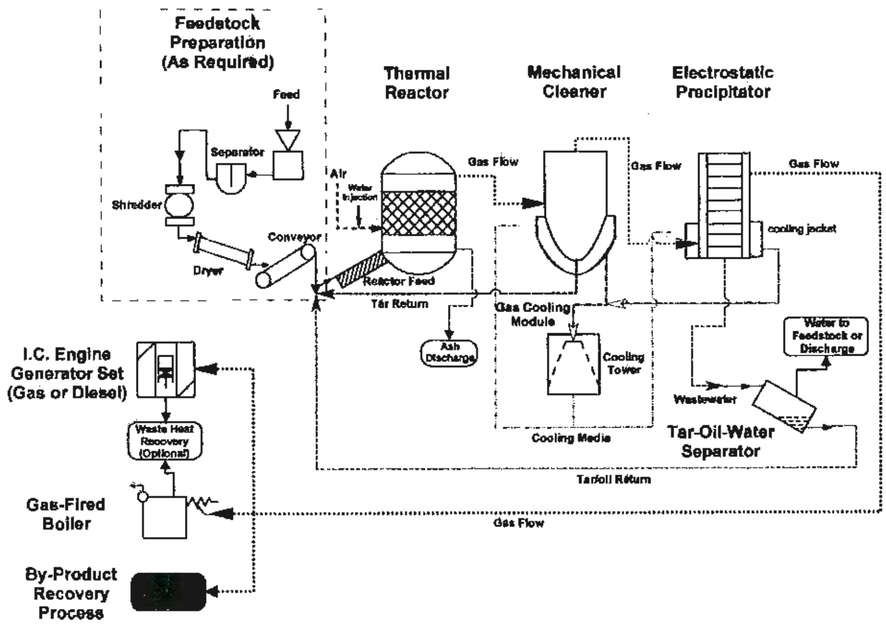

Fig. 2 – Thermogenics #103 Process Flow Sheet for electrical power, steam generation or by-product recovery

The gasifier has operated more than 750 hours to date. The efficiency is 75-82%, depending on feedstock characteristics. The gasifier produces 1350-2,000 SCM/h gas with an energy content of 6.9 MJ/Scm^3 from wood, 13.8 MJ/Scm^3 from tires. Particulate content is less than 10 ppm and tar content is very low due to a novel cleanup system.

The gas has been tested in spark ignited and diesel (with 1-5% pilot fuel) engines and boilers. The fuel can be any organic material less than 5 cm maximum dimension and less than 30% moisture content with over 11 kJ/g energy content. Extensive data are available on wood, MSW, wastewater sludge and waste tires.

Three models are available; Model 103, ½ ton/hr for $450,000; Model 104, 1 ton/hr; and model 106, 3 ton/hr, (FOB Beaumont, Texas). These are suitable for producing 300-400, 600-800 and 1800-2400 kW. The gasifier has:

- Multi-fuel capability
- 2-3:1 turndown ratio
- Quick startup, discontinuous operation simple
- Gas directly usable in standard IC engines

- No grate, fluidizing medium or other internal process mechanisms

The gasifier was developed in cooperation with Sandia National Laboratories and the State of New Mexico, and can use Sandia's Passive Afterburner. The systems will sell for about 20% of the cost of other equivalent capacity systems and will produce large volumes of hot (>550°C) clean exhaust gas for drying, process heat, steam production etc. The system is being investigated for Stirling engine power production technology.

Thermogenics has a marketing agreement (for Canada) and a technical collaboration agreement with Ontario Hydro Technologies from Toronto. They have completed a 1,000 lb/hr system for rural use (off-grid) power. A 6,000 lb/hr unit is under construction.

Thermogenics has a cooperative test program with Sandia National Laboratories, also located in Albuquerque. A new series 300 gasifier for producing synthesis gas by pyrolysis with 2000°F superheated steam is now being tested.

GENERAL REFERENCES

The National Renewable Energy Laboratory has sponsored a series of conferences that contain extensive reports on all aspects of biomass conversion including gasification. See for instance

[Overend, 1997] **Proceedings of the 3rd Biomass Conference of the Americas**, Ed. R. Overend and E. Chornet Eds, Pergamon, p. 551, 1997.

[Overend, 1999] **Proceedings of the 4th Biomass Conference of the Americas**, Ed., R. P. Overend and E. Chornet, Pergamon, 1999.

In addition, the thermochemical conversion community holds meetings every 4 years on all aspects of thermal conversion. (The next meeting will be in Austria in Aug. 2000.)

[Bridgwater, 1993] **Advances in Thermochemical Biomass Conversion,** Ed. A. V. Bridgwater, , Blackie Academic Press, 1993.

[Bridgwater, 1996] **Developments in Thermochemical Biomass Conversion,** Ed. A. V. Bridgwater and D.G.B. Boocock, Blackie Academic Press, London, 1996.

CHAPTER 5

GASIFIER RESEARCH ORGANIZATIONS

CONTENTS

Introduction

The world of gasifier research is in continual ferment, with institutions coming and going all the time. This book has been in preparation for four years, so some of these entries are new, some older. Sometimes research gasifiers are developed for a larger scale commercialization; sometimes they re developed full scale. Sometimes the developers leave the institutional shelter and become commercial. A perfect "snapshot" of all groups today would be out of date tomorrow. A much larger list of research organizations is included in the data base in Chapter 2. For this reason we recommend visiting our database on our website at www.webpan.com/bef for latest postings.

In this section we introduce a number of research groups working on gasifiers. We have lumped these together because there is considerable crossing of the line both ways - institutions inspire individuals to get into the business; existing businesses convince institutions that they should work in this field. It is not always clear which chapter each organization belongs in, so look also in Chapter 3.

In some ways these are the locations of the most exciting events in gasification. The new experimentation and thinking at the institutions plus the experience of manufacturers in the field provides the paths for improvement in the future. However, while we mention specific examples of typiacl work, readers desiring information should contact the organization. They often have a publication section that can send more recent reports on the work.

We offer here our apologies to the dozens of other gasifier organizations not represented here because we did not know of them or because they are quite similar to those given.

5.1 *The Biomass Energy Foundation*

Contact: Thomas Reed

Address: 1810 Smith Rd., Golden, CO 80401

Telephone: 303 278 0558

Fax: 303 278 0560

Email: reedtb2 @ cs.com

WWW: www. webpan. com/BEF

The Biomass Energy Foundation, BEF, was founded in 1984 by Dr. Harry LaFontaine. Harry built gasifiers during World War II as a cover for his nighttime activities in the Danish Underground. When the "energy crisis" struck in 1974, Harry gave lectures and demonstrations on gasification in many universities around the East.

In 1982 he set up a 501-3-C (not for profit) foundation for his activities in biomass. I met Harry in 1985 and he invited me to be a member of his board of directors. At that time I began to publish books at the Biomass Energy Foundation.

In 1994 Harry died (at age 80) and left the BEF to me, Dr. Thomas Reed, to pursue it's original purposes. We engage in gasification research, consulting, publishing and travel activities in the field of biomass, specializing in gasification. We are able and willing to sponsor projects related to these purposes.

Currently we are working with the National Renewable Energy Laboratory, NREL, and the Community Power Corporation to develop a 25 kW Modular Biomass Power System to serve the huge market of those currently unserved by the large utilities. We are also developing a "turbo wood gas stove" for cooking in the developing countries.

Biomass energy and particularly biomass gasification is a field where publications are often difficult to find. We make available information on biomass, especially gasification, at reasonable prices. (See book list at end.) We will also make available at $0.15/page other papers from our extensive library of technical papers on gasification dating back to the turn of the century. We also act as a clearinghouse to locate technical assistance for biomass projects. We also publish other technical books.

See also our posting in Chapter 4 for current work and our website for continual updatings.

5.2 *BTG (The Biomass Technology Group)*

Contact: Harrie Knoef

Address: PO Box 217, 7500 AE Enschede, Netherlands

Telephone: 31 53 489 2897

Fax: 31 53 489 3116

Email: knoef.btg@ct.utwente.nl

WWW: http://btg.ct.utwente.nl

The Biomass Technology Group B.V. is an independent private firm of consultants, researchers and engineers based in Enschede, The Netherlands. BTG is a leading organization in the field of energy production from biomass and waste.

Started as specialists in small-scale biomass gasification in 1979, BTG has built up extensive experience in environmentally sound technologies for the conversion of biomass (residues or fuel crops) and waste. Activities range from fundamental research to commercial technology application. BTG has experience in the field of Greenhouse Has (GHG) Mitigation, Life-Cycle Analysis, CO_2 Abatement and Incremental Cost Analysis, for example in the GEF/World Bank Ivory Coast Biomass Power Project. In 1995, a Dutch consortium formed and led by BTG tendered for and was awarded a UN/OPS service contract for the provision of support to UNDP/GEF in Energy and Climate Change.

BTG has field experience in over 50 countries in all continents. Recent Asian countries experience includes: China, India, Indonesia, North Korea, Philippines, Sri lanka, and Vietnam.

Technology Expertise

- Gasification
- Pyrolysis
- Carbonization
- Combustion
- Densification
- Cookstoves

Fields of Activities

- Research and Development
- Project engineering and implementation
- Sector and technology assessments and feasibility studies
- Project identification, development and financing

Please visit their WWW page for further information

5.3 *CAAMS (The Chinese Academy of Agriculture Mechanization Sciences)*

Contact: Gao Xiansheng, Professor CAAMS

Address: No. 1 Beishatan, Deshengmen Wai, Beijing 100083, China

Tel: 86 1 201 7131

Fax: 86 1 201 7326

I have known Prof. Gao Xiansheng since 1985 when he visited me at NREL and we discussed various gasifier designs. In 1992 I visited Prof. Gao at CAAMS to evaluate Chinese gasifiers for the Rockefeller Foundation. During my visit we traveled in suburban Beijing to see two gasifier manufacturing plants and visit several gasifier installations. Most of the following is taken from my report to the Rockefeller Foundation at that time. (Note: Prof Gao has since retired, but CAAMS is still interested in gasifiers.)

THE BIOMASS DOMESTIC GASIFIER COOKING STOVE (BDGCS) FOR VILLAGE COOKING:

I visited three households using a Biomass Domestic Gasifier Cooking Stove (**BDGCS**) and saw demonstrations of cooking with the gasifier-stove by several women. The gasifier operates outside the cooking shed. The gasifier takes about 1 minute to start and produces more than enough gas for a two burner stove. It will boil 5 liters of water in 12-15 minutes.

The gasifier consumes 4 kg of biomass (corn cobs, wood waste, straw etc.) per hour to produce 12 m^3 of gas/hr. The gas burning stove produces no obvious emissions and has an estimated cooking efficiency of 35% (against a typical cooking efficiency of 12% for direct combustion of the same biomass).

I visited the BDGCS factory in Shun Yi County (suburban Beijing) where the stoves are made and saw over 50 stoves ready for shipment. The stove-gasifier is simple in design and could be made in most rural shops in other countries, especially if certain key parts were supplied from a central facility. The stove is said to cost $150. I talked to the factory-manager and he is interested in and capable of selling stove-gasifiers or licensing the stove-gasifier technology to other developing countries.

(The BDGCS is still considered to be in the advanced testing stage by CAAMS. Contact them for current status.)

China has a record in the last decade of massive development of Biogas (digester gas from manure) systems in rural areas (over 10 million estimated). The thermal gasification technology has many features in common with Biogas and can build on both the positive and negative aspects of that experience. While Biogas requires primarily manure and a warm climate for anaerobic digestion, the BDGCS stove-gasifier system can use most forms of biomass and can operate in all weather.

The Chinese farm wives we visited, who previously have cooked meals over open coal, straw, dung, cobs or wood, are very enthusiastic about cooking with the much cleaner, more efficient BDGCS. The gasifier-stove technology could have a major impact on cooking in all developing countries. It uses up residues that are otherwise burned, creating pollution. It reduces deforestation, and the use of fossil fuels.

An Achilles heel of the gasifier is that it requires 100 watts of power to operate the blower - and power in China is very interruptible.

THE ND-600 INDUSTRIAL GASIFIER FOR INDUSTRIAL PROCESS HEAT:

I visited several furniture factories South of Beijing that are currently using the ND-600 gasifier to dry lumber in a kiln. The gasifier consumes 50-60 kg/hr of wood wastes to produce about 120 Nm^3 of low energy gas (60,000 Btu/hr). This is burned directly for wood drying in a kiln. The gas can also be used for producing steam in a boiler or for other process heat.

Operation of the ND-600 requires partial attention from one man to load wood. Several gasifiers can be operated by one man during an eight hour shift and they are typically operated 24 hours/day for extended periods. The gasifier can use wood waste including sawdust, corn cobs, straw and other agricultural residues.

I visited the factory making the ND-600 in Huai Rou County and saw many gasifiers being made. About 200 of these gasifiers are currently in operation in China and the factory received an order for 80 more while I was there. The gasifier costs $1500.

I talked extensively to the managers of the factory about their plans. They (and China) would be interested in exporting the gasifier to other Asian developing countries or licensing factories in other countries to build the gasifier.

This gasifier is now a major supplier of process heat and drying energy in China. It has the potential to reduce deforestation and the use of fossil fuels.

Figure 1 - The new improved ND-600 gasifier for process heat, showing (left to right) the gasifier, a pre-burning chamber to ignite the combustible gas for startup and the combustion chamber, and a vessel containing the hot combustion gases.

I also talked extensively with personnel at CAAMS about other developments of gasification for power generation that are now being actively pursued. A 20 kW gasifier system is now under test. However, it is not yet ready for commercialization.

While the gasifiers visited were very impressive, further improvements in use should be made relative to controlling fuel moisture content and particle size. Lack of attention to these factors has been the downfall of many former systems.

I received a letter from Prof. Gao March 4, 1998 with pictures of the latest version of the ND-600 shown in Fig. 1. It produces 128 m^3/hr of gas with a heat energy of 630 kJ of 5 MJ/m^3. It consumes 50-55 kg/hr and has an efficiency of 75%.

FUTURE PLANS

China is developing a "county enterprise" system which gives considerable freedom to counties to manufacture and sell various products. I visited the two county enterprise systems involved in manufacture of the gasifiers and observed the manufacture of the two gasifiers. A large inventory of each type was on hand indicating that both are near commercial.

In each case I met with the country manager and his staff. They expressed a strong interest in having me help them to market the gasifiers in other developing countries.

The Chinese Academy of Agricultural and Mechanization Science (CAAMS) was my host while I was in China. They serve a function similar to our National Laboratories and are working closely with the counties in production testing and marketing the gasifiers.

The gasifiers are now being distributed and sold in China on a limited basis, and their use will probably expand very rapidly in China. With little modification they could be used to provide stored gas for Gas-Refrigerators, Gas Mantle lights, and water heating.

If the gasifiers are successful in China, it would be desirable to spread the technology to other developing countries. This would require further testing for other countries and training manuals. Manufacture of the gasifiers for export, or licensing the technology in other countries is of great interest to China. However, there are legal barriers to China's dealing with other developing countries. One possible method of solving these problems would be for an entity in the U.S. to become interested and become a trusted intermediary. Twente University in the Netherlands has performed this function for rice hull gasifier development in and outside Indonesia.

5.4 *Danish Technical University*

Contact: Ulrik Henriksen

Address: Technical University of Denmark, Bld. 403, DK-2800 Lyngby, Denmark

Telephone: 45 45 93 37 57 X 4156

Fax: 45 45 93 57 61

In October, 1996 I visited the Danish Technical University. They are working on straw combustion using pyrolysis followed by combustion. There are also projects on small gasifiers and clean cooking stoves.

For further information, visit www.dtu.dk

5.5 *DKTechnik, (Denmark)*

Contact: Soren Houmoller, Henrik Jakobsen

Telephone: 45 39 69 65 11

Fax: 45 39 69 60 02

E-mail: houmoller@dk-teknik.dk

WWW: www.sh.dk

Address: dk-TEKNIK, Gladsaxe Møllevej 15, 2860 Søborg, Denmark

Activities: Danish Energy Agency; fluidized bed gasifiers, stratified downdraft gasifiers, straw gasification

Soren Houmouller studied a fluid bed gasification concept to convert straw, wood or other biomass to a gas to be combusted in an internal combustion engine. They started from an existing, successfully operating two stage fixed bed pyrolysis and gasification concept and built a new fluid bed version which is more compact and easy-to-scale. The new design transformed the two stage fixed bed process to fluid bed. It was built and operated. Preliminary results were presented in Banff, Canada, and they received the "Poster Award First Class" in Copenhagen in June 1997. They are now doing feasibility studies on the gasifier.

Henrik Jakobson is working on a 150 kW stratified downdraft gasifier and has achieved 100 hours of operation [Jakobsen, 1999].

Continuing results are posted on Mr. Houmouller's home page on the WWW or at www.sh.dk/~cbt/sh/fluidbed/openpapar.htm.

REFERENCES

[Jakobsen, 1999] Jakobsen, H. H., "Air Staged Open Core Gasifier for Forest Wood Chips with Engine Operation", report from dk-Teknik, Aug. 1999.

5.6 *Indian Institute of Science, Bangalore*

Contact: Prof. H. S. Mukunda

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India has created a number of Institutes of Technology to provide education and research in modern technology; IIT Delhi; IIT Bombay etc. They have also created the Indian Institute of Science in Bangalore which houses major Indian Aerospace research. Prof. Mukunda is head of a large group dealing primarily with improving smaller scale gasification for use in India [Gayathri, 1999].

In October 1996 and (again in October 1998) I visited the gasification group and saw a number of gasifiers, stoves, and turbines under development. I sat around the conference table for 2 ½ days and asked and answer questions with a dozen or so scientists in the group. Because of the aerospace background they have a deeper understanding of combustion and gasification processes than most others in the field. Rather than discuss in detail all the work, here is a sample list of some of the papers to give a flavor of the fundamental nature of some of the work at IISc.

The Flame Speeds, Temperature And Limits Of Flame Propagation For Producer Gas-Air Mixtures: Experimental Results

Theoretical Calculations Of The Limits Of Flame Propagation For Producer Gas Mixtures

Fundamental Combustion And Gasification Aspects Of Biomass And Biomass Derived Gaseous Fuels

On The Combustion Of Wood-Char Spheres In O_2/N_2 Mixtures

Fluid Dynamic Studies On Ejectors For Thermal Applications Of Gasifiers

Lest one think that the work is only theoretical, here is a sample of practical developmental papers:

Portable Single-Pan Wood Stoves Of High Efficiency For Domestic Use

Open Top Wood Gasifiers

IISc-Dasag Downdraft Gasifiers For Co-Generation Plants

Results Of An Indo-Swiss Programme For Qualification And Testing Of A 300kw Iisc-Daasag Gasifier

A major problem in gasification is tar in the gas, greatly increasing the cost and complexity of gasifier systems, so a "tarless" gasifier is the holy grail of gasification. IISc has developed a gasifier, the IISC-DASAG gasifier, that produces gas containing less than 100 ppm tar. One of these gasifiers was shipped to Switzerland, installed and tested there with similar results.

In addition to the gasification activities, Mrs.V. Gayathri publishes the Biomass Users Network (BUN-India) newsletter, free on request. They also maintain a home page for their work where many of the above papers are available. In summary, IISc is a major gasification laboratory for small and midsize gasifiers.

References

[Gayathri, 1999] Many papers are available from IISc. Write to the department administrative assistant, V. Gayathri at gayathri@aero.iisc.ernet.in for details.

5.7 *Indian Institute of Technology, Bombay*

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Prof. Parikh is a combustion specialist in the Mechanical Engineering Department at IIT Bombay. For over a decade she has been retained by the Government of India, Ministry of Non-conventional Energy Sources(MNES) to do research in gasification and to evaluate various gasification systems [Parikh, 1999].

I visited Prof. Parikh for four days in 1990 and was very glad to return for three days during my 1996 trip to India. She has produced over a dozen Ph.D. and Masters theses. Her equipment and instrumentation far exceeded anything I have seen in other gasification research labs, including my own DOE lab at SERI/NREL in the 1980s.

A few titles are:

1. Dual-fuel Operation of Compression Ignition Engines Using Wood based Producer-gas as Supplementary fuel.
2. Design, Development and Testing of a 15kW Biomass Gasifier System for Engine Applications.
3. Study of Tar and Particulates in Biomass based Producer-gas.
4. Designing and Establishing Test Facilities for Biomass Gasifier Engine Systems.
5. Design, Fabrication and Testing of a Continuous Feed Type Rice Husk Throatless Gasifier.
6. Design, Development and Testing of a 30 kW Updraft Biomass
7. Performance Evaluation of Gasifier engine-system Operating on Dual-fuel mode.
8. Design and Development of an Industrial Burner with Producer-gas as fuel.
9. Performance Evaluation of Rice Husk Gasifier.
10. Feasibility Study of Using an Updraft Gasifier for Air Gasification of rice Husk.
11. Parametric Optimization of Rice Husk Gasifier.
12. Effect of Utilization of Producer-gas on Operation and Maintenance Requirements of C.I. Engines (Wear Studies).
13. On Proximate Analysis Producers for Biomass and Effect of Heating Rates on Biomass Devolatization.
14. Performance Evaluation and Optimization of S.I. Engine for use of gaseous fuel.
15. Development and Testing of Producer-gas S.I. Engine for Power

Generation.

16. Fuel Spray Analysis at Low Injection Rates using Malvern Particle Size Analyzer.

I was an examiner on one thesis, "On Biomass Gasification Process and Technology Development", by S. A. Channiwala. The thesis contained the most complete collection of biomass analyses in print. I subsequently included this with some modification in our "Atlas of Thermal Properties of Biomass and Other Fuels" [Gaur, 1995, 1998]. A PhD thesis on conversion of diesel engines to spark ignition has just been completed by Shashikantha and I await my copy with considerable interest.

The work carried out at IIT Bombay has made many original contributions to the area of dual-fuel engines. A change in the approach is now professed regarding percentage diesel replacement (%DR). Maximization of %DR is not considered advisable on the basis that the minimum diesel quantity is to be decided not by combustion considerations alone, but also the hydraulic characteristics of the fuel injection system. At fuel rates lesser than no load rate, the injection process becomes inconsistent with high degree of cyclic irregularities. This leads to unstable and inefficient operation of the dual-fueled engine. Operational instability at very low diesel rates is also contributed by poor atomization and other spray characteristics.

High level of inter-cylinder non-uniformity of injection and spray parameters at lower injection rates are well established facts. These also affect the performance of dual-fuel engines.

Such loss of performance is generally wrongly attributed to producer-gas and/or the engine design. Performance of dual-fuel engines, in terms of capacity realization, emissions and efficiency is immensely influenced by fuel injection process parameters. In view of these facts, the generally pursued approach of maximization of %DR needs to be given up and care has to taken that the minimum pilot diesel rate in a dual-fuel engine is not below the idling quantity.

Prof. Parikh has collected over 3,000 references for a data base, "State of the Art of Research on Gasification of Biomass", SARGOB, which we hope to have available on the World Wide Web.

IIT Bombay is one of the major laboratories in smaller scale gasification and particularly engine operation.

[Gaur, 1995, 1998] Gaur, S. and Reed, T. B., "An Atlas of Thermal Data for Biomass and Other Fuels", The National Renewable Energy Laboratory, NREL/TP-433-7965, and "Thermal Data for Natural and Synthetic Fuels, M. Dekker, May, 1998.

[Parikh, 1999] For further information on the above topics, write to Prof. Parikh at parikh@me.iitb.ernet.in

5.8 *KTH (Kungl Tekniska Hogskolan, the Royal Institute of Technology), SWEDEN*

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The Swedish government has enthusiastically supported biomass energy for several decades because they have enormous forest resources and are major producers of paper and lumber. In October 1996 I spent a day at the prestigious KTH listening to presentations of their work in the fields of gasification and combustion and visiting their well equipped laboratories. They have a very impressive list of publications over the last decade and are a major research institution in all aspects of gasification [KTH, 1996].

The use of biomass with gas turbines is hampered by the very small content of sodium and potassium in the gas. In particular I remember seeing a surface ionization probe being tested that could measure less than 1 ppm of sodium and potassium.

In a brochure describing the gasification research at KTH 36 papers are listed, such as:

Rapid Pyrolysis Of Bagasse, Sugar Cane And Banana Agricultural Residues

Equipment For Cracking Of Pyrolysis Gas From Biomass

Characterization Of Tars From Coal/Biomass Gasification

Steam Reforming With Nickel-Based Catalysts On Gas From Biomass Gasification

References

[KTH, 1996] "Gasification Research KTH", 21 page brochure preparedby the Department of Chemical Technology

5.9 *National Renewable Energy Laboratory (NREL, formerly SERI)*

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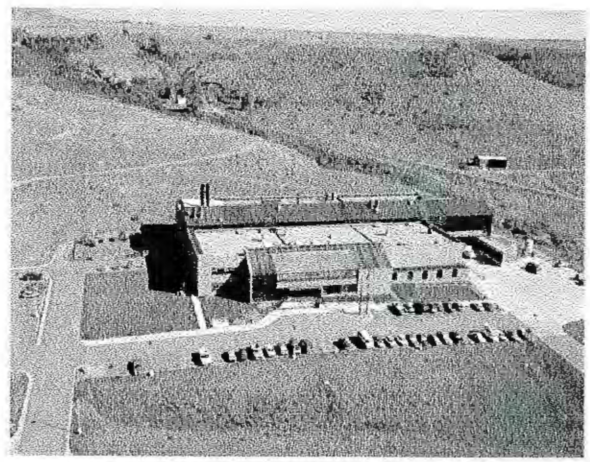
I joined SERI in 1977 and worked in the field of gasification of biomass there until 1986. We built and studied a high pressure oxygen gasifier which was later commercialized by Syngas Inc. Details of this work are available [Reed,1988].

Currently the biomass energy division operates The Thermochemical User Facility, available to industry for testing various aspects of gasification. They also have an engine laboratory for testing small power systems. There is a unique Molecular Beam Mass Spectrometer for studying the organic and inorganic vapors found in tars, oils and gasifiers.

The National Renewable Energy Laboratory (NREL), the nation's leading center for renewable energy research, was established by the Solar Energy Research and Development Act of 1974.

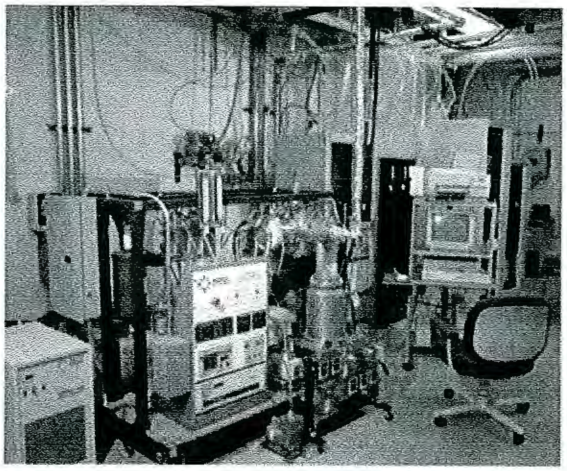
Originally called the Solar Energy Research Institute, NREL began operating in July 1977 and was designated a national laboratory of the U.S. Department of Energy in September 1991. NREL is developing new energy technologies to benefit both the environment and the economy by conducting research in about 50 areas of scientific investigation. Research areas include photovoltaics, wind energy, biomass-derived fuels, chemicals, and electricity, energy-efficient buildings, advanced vehicles, solar manufacturing, industrial processes, solar thermal systems, hydrogen production, fuel cells, superconductivity, geothermal and waste-to-energy technologies. NREL's mission is to lead the nation toward a sustainable energy future by developing renewable energy technologies, improving energy efficiency, advancing related science and engineering, and facilitating commercialization.

The thermochemical conversion of renewable energy feedstocks has been investigated at NREL since its inception. NREL engineers and scientists in the Chemistry for Bioenergy Systems Center have diverse expertise associated with converting feedstocks into valuable products, such as fuels, chemicals, and electricity, as well as the analytical techniques and instrumentation to characterize the processes and thus provide private sector collaborators with information on process control.



Field Test Laboratory Building at the National Renewable Energy Laboratory, Golden, Colorado.

One of these unique analytical techniques, direct, free-jet expansion, molecular beam mass spectrometry (MBMS), was developed by Midwest Research Institute, transferred to SERI by Tom Milne, and its development continued at SERI and NREL. Laboratory study of high-temperature, atmospheric-pressure chemistry involving unstable, reactive and condensable species has been a significant part of NREL's effort. The MBMS is used for studies of a variety of ambient pressure reactive systems. Examples include solar and thermal destruction of toxic gases; selective pyrolysis of mixed plastics to recover valuable chemicals; catalytic reaction studies, such as cracking and steam reforming of gasifier tars; characterization of alkali metal vapors from biomass combustion; biomass and black liquor gasification; and analytical pyrolysis of biomass feedstocks and products for rapid screening of composition. The extensive use of multivariate analysis of complex mass spectra is an integral tool in interpretation of MBMS data and in providing process conditions that minimize environmental impacts of intermediates and products.



NREL's Transportable Molecular Beam Mass Spectrometer for use by industry and collaborators. On the left, performing comparative emissions from diesel and biodiesel engine tested in Denver's RTD laboratories and, on the right hand side, in the Institute of Gas Technology high pressure gasifier in Chicago.

Several unique, direct, free-jet, MBMS sampling systems are used at NREL. One is a laboratory instrument with a triple quadrupole mass analyzer for tandem-mass spectrometric identification of isobaric ions. NREL also has a single photon ionization, molecular beam sampling, time-of-flight mass spectrometer system and two transportable systems (TMBMS) with single quadrupole mass analyzers. The transportable systems are designed to permit field sampling of effluents, exhausts, stack and process vapors and gases, etc. as well as for use in the laboratory. Efforts are currently focused on making the transportable systems more compact and less expensive to enhance the capability and availability of MBMS for on-line process monitoring and, ultimately, process control.

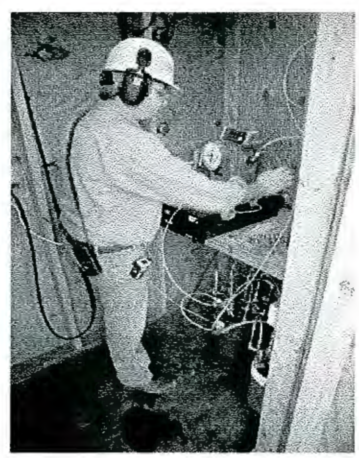
In addition to the mass spectrometric on-line instruments being developed and evaluated, near infrared spectroscopy is also being developed for the rapid, on-line characterization of biomass physical and chemical properties. NREL is also performing research that would make it possible to measure mechanical properties on standing timber from chemical spectroscopic information. Infrared spectroscopy is an indispensable method for both qualitative and quantitative analysis of organic substances. Various infrared spectroscopic techniques have been used to study solid wood and various constituents of wood, the mechanisms of delignification in pulping, and the aging processes of wood. In a search for on-line measurement techniques for characterizing wood and paper we have developed a Near InfraRed (NIR) spectral technique that can be used to analyze samples as rapidly as conventional IR transmission spectroscopy rapid without extensive sample preparation. While the NIR spectra are not as rich as the fingerprint region of the mid-IR range techniques, modern multivariate statistical techniques have made it possible to enhance information extraction from these spectra and to use NIR for quantitative analysis. The principal advantages of the method are that the instrumentation is less expensive than mid-range instruments and spectra can be obtained on solid materials rapidly with little or no sample preparation. For these reasons NIR spectroscopy seems very-well suited for on-line applications.

The Chemistry for Bioenergy Systems Center at NREL, through the support of the U.S. Department of Energy, also provides a state-of-the-art Thermochemical Users Facility (TCUF) for converting renewable feedstocks into a variety of products, including electricity, high-value chemicals, and transportation fuels. The TCUF can be configured to accommodate the testing and development of various reactors, filters, catalysts, or other unit operations. Scales range from 0.1 kg/hr for bench-scale reactors to 20 kg/hr in the new Thermochemical Process Development Unit (TCPDU). Users can obtain extensive performance data on their process or equipment, quickly and safely with a modest investment of time and money.

Customers have available NREL's experienced staff of scientists and engineers to plan and conduct experiments and interpret data using the latest statistical techniques. Customers make timely and informed business decisions based on sound engineering and scientific data to rapidly get their product to the marketplace. Many companies have directly benefited from access to NREL's reactors and analytical capabilities.

NREL's TCPDU and laboratories can analyze products on-line over a wide spectrum of chemical compositions using dedicated analytical instruments operated by trained technicians and scientists. The TCPDU's state-of-the-art process control system is interconnected with the analytical instruments' control computers to create a single integrated database. About 1000 input/output points are monitored for both engineering and chemical analysis data. Chemometric computer analysis of all collected data can be used for rapid process optimization.

A recent addition to NREL's TCUF is an engine test cell for investigating the challenges associated with integrating biomass gasifiers with power generation equipment to form integrated gasification power (IGP) systems. In addition to fuel cells, IGP systems include gas turbines, modular turbines, as well as Stirling and diesel engines. These devices can all be integrated with biomass gasifiers to make efficient, low CO_2-emitting power generating systems. NREL can simulate a variety of gasification conditions and test, side by side various power generation units.



NREL's staff provide technical assistance to private sector partners. On the left, Ralph Overend at the Vermont gasification site (flare and feeding systems shown) with FERCO's CEO, Mr. Milton Ferris, Burlington Electric Department's Mr. John Irving, station manager, and Mr. Mark Paisley, coinventor of the concept from Battelle. On the right, Mr. Joe Patrick from NREL is shown conducting sampling and analysis at the Vermont plant.

Market and regulatory factors will dictate which integrated systems have the best cost and environmental benefits for a given application. Hence, NREL is endeavoring to clarify and demonstrate these cost and environmental trade-offs by quantifying the contaminant species in syngas that prevent reliable operation of power generating equipment. NREL can then develop and test reactors and system configurations that remove those contaminants, and demonstrate their performance by operating IGP systems.

NREL also uses two types of process analysis to provide direction, focus, and support to the development and commercialization of various biomass thermochemical conversion technologies. Technoeconomic analyses (TEA) are performed to determine the potential economic viability of a research process. The economic feasibility of a project can be assessed by evaluating the costs of a given process compared to the current technology. These analyses can therefore be useful in determining which emerging technologies have the highest potential for near-, mid-, and long-term success. The results of a TEA are also useful in directing research toward areas in which improvements will result in the largest cost reductions. As the economics of a process are evaluated throughout the life of the project, advancement toward the final goal of commercialization can be measured. Technoeconomic analyses performed in previous years have determined the technical and economic feasibility of various biomass-based systems, including direct combustion, pyrolysis, gasification combined cycle, and integrated gasification fuel cells.

The second analysis tool, lifecycle analysis (LCA), is an analytic method for identifying, evaluating, and minimizing the environmental impacts of emissions and resource depletion associated with a specific process. When such an assessment is performed in conjunction with a technoeconomic feasibility study, the total economic and environmental benefits and drawbacks of a process can be quantified. Material and energy balances are used to quantify the emissions, resource depletion, and energy consumption of all processes required to make the process of interest operate, including raw material extraction, processing, and final disposal of products and by-products. The results of this inventory are then used to evaluate the environmental impacts of the process so that efforts can be focused on mitigating these effects. LCA studies have been conducted on a biomass gasification combined cycle system, three coal-fired power plant systems, direct combustion systems and a biomass/coal cofiring system. LCA studies of distributed and small-scale biomass systems, and natural gas systems are planned for the near future.

These life cycle studies have enjoyed a very significant peer review and involvement of a variety of modeling experts and power generation experts. The life cycle analyses provide a good way to tie the environmental benefits of biomass power systems and other biomass uses with conventional energy and materials production, economic development, and sustainability.

5.10 *Ministry of Agriculture (MOA) of the People's Republic of China*

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The U.S. Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL) has been working with the Ministry of Agriculture (MOA) of the People's Republic of China under Annex I of the Energy Efficiency and Renewable Energy Protocol signed between the U.S. and CHina in 1995. This work has resulted in: the assembly of a significant body of information on biomass resources; a description of China's technological capability in some of the biomass conversion areas; and an initial assessment of the potential of some of the biomass and bioenergy systems.

The data generated has been published at NREL in English [Overend, 1998] and in China as a bilingual 3 volume document with a CD-ROM [MOA/DOE, 1999]. This project is continuing under the direction of Dr. Ralph Overend in the U.S. and Mr. Bai Jinming of the MOA and Professor Zhang Zhengmin, Ms. Dai Lin and Ms. Li Jingmin of the Energy Research Institute in China.

Ms. Dai Lin is spending two months at NREL. I hope to see her in a week or so.

REFERENCES

[Overend, 1998] Overend, R., "Biomass and Bioenergy in China in 1998", National Renewable Energy Draft Report NREL/SR-570-24860, 1998.

[MOA/DOE, 1999] "Biomass Energy Conversion Technologies in China: Development and Assessment", Eds. Dai Lin, Li Jingming and R. Overend, China Environmental Science Press, Beijing 1999.

5.11 *Shandong Energy Research Institute (Village Gasifier Project)*

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Half the population of the world lives in villages with under 1,000 souls, typically without electricity, gas, running water or refrigeration. These people generally burn various forms of biomass, inefficiently and toxically. In Shandong province alone 67 million people live in 90,000 villages. The Shandong Academy of Sciences has developed a gasifier that makes and stores producer gas that could, in principle, supply all these "necessities of civilization" from biomass. The Chinese Ministry of Agriculture and the U.S. Department of Energy –NREL, have a joint program to implement biomass use both at the village and the national level. (See Ministry of Agriculture entry.)

For village gasification, corn straw, wheat straw or other biomass with MC <20% are reduced to 10-15 mm lengths and fed into a gasifier by a screw feeder. A blower draws air through the gasifier, through the cyclone, cooler and filter and sends the gas to the gas holder. The negative pressure at the gasifier permits it to operate with an open top, greatly aiding loading and poking. The gas holder balances the production and consumption of gas and serves as a manostat to maintain a modest pressure for distribution. The gas is sent to the network of pipelines and distributed to every household for cooking [Sun Li, 1995,1997].

China produces 600 M tons of straws per year, much of which is burned in the field, and so the government has been particularly interested in using crop straws for village energy. The bulk densities of several biomass materials are shown in Table 1 where it is seen that the straws have very low density.

Table 1 - Bulk Density of selected biomass fuels

FUEL	Bulk Density - kg/m^3
Hardwood	220
Softwood	250
Charcoal	150-230
Corncobs (11% MC)	304
Cotton Straw (23% MC)	340
Corn Straw (10-15 mm)	67
Corn Straw (10-15 mm)	25

The small bulk density makes the collection and storage of the feed difficult for straw. The heat capacity in the oxidation zone is also greatly reduced and results in unsteady gasification. The angle of repose of corn straw chopped to 10-15 mm is 90° and even greater for wheat straw, so that the straw does not move easily down due to gravity, causing bridging and ratholing. After pyrolysing the volume of corn straw is reduced 50-55% and wheat straw is reduced 80% due to the softness of the straw charcoal. Cropstraws also have severe slagging problems due to their high ash content. A number of other fuels have also been tested with positive results.

The research at Shandong has been conducted to overcome these problems. Two models of cropstraw gasifiers named XFF-1000 (1000MJ/h) and XFF 2500 (2500 MJ/h) were developed and tested with the results shown in Table 2. The units produce a low-Btu gas with tar and dust content below 100 mg/Nm^3.

Table 2 - Properties of the XFF straw gasifiers

	XFF-1000	XFF-2500
Gas output, Nm^3/h	216	524
Gas LHV, kJ/Nm^3	5327	5215
Energy output, MJ/h	1151	2733
Conversion efficiency, %	73.9	73.1
Gas-Feed ratio, m3/kg	1.90	1.92

Three demonstration systems have been built and put into use and four more systems are now being built. The first system supplying gas for 94 households was built in October 1994 and has run for 16 months. The systems serve between 90 and 268 households, supplying 540 to 1500 Nm^3/d . The gasholders are all 250 Nm3 except one of 80 and one of 280. They maintain a pressure of 30 cm water pressure (12 inches of water column). The longest pipeline s 680 meters. They consume 280 to 800 kg/day of straw. The average family of 3.8 people consumes 6 Nm^3 of gas per day, primarily at mealtime. The gasifier is designed to operate through lunch and dinner which decreases the size of gasholder required, the most expensive part of the system.

Each system has a cropstraw storage field, a gasification station and a network of pipelines. Several liquid collectors are located in the pipelines to remove the water that condenses in the pipe occasionally. The pipes are made of PVC and PP and placed underground.

Many people believe that the low heating value of producer gas will produce low temperatures in combustion, but the Shandong Institute correctly shows that the low heating value of producer gas does not need to be as much of concern as it often is. This is because a large amount of air is mixed with all fuel gases for stoichiometric combustion, after which the variations in energy content are much smaller. Calculations of the maximum combustion temperature for correct mixtures of various fuel gases are shown in Table 3.

Table 3 - LHV of various fuels and their flame temperatures.

	Gas LHV MJ/Nm^3	Stoich Air/Fuel m^3/m^3	Mixture LHV MJ/m^3	Combustion Temp °C
Natural Gas	36.5	9.64	3.44	1970
Coke Gas	17.6	4.21	3.38	1998
Mixed gas	13.9	3.18	3.31	1986
Biogas	21.2	5.65	3.19	
Generator gas	5.7	1.19	2.61	1600
Straw Gas	5.3	0.9	2.80	1810

In the table it is seen that the heating value of the stoichiometric mixture does not have a major effect on the flame temperature of the gas, even though there is a significant reduction in power for engines and in cost for long distance pipelines for producer (generator) gas. In addition, Chinese farmers typically have a high population density in villages, 10,000 people/km^2 Vs 3000 people/km^2 in a city such as Hinan, capital of Shandong Province, so that distribution distances are not large.

The cooking efficiency tested on a producer gas stove was 50-53%. The efficiency of the gasifier system was 73%. Therefore the overall cooking efficiency was about 37%. Conventional stoves burning straw directly have an efficiency of 10% and a new style is 15-20% efficient.

The cost of the demonstration systems ranged from 160-476 thousand yuan or 1800-2700 yuan/household. A typical family has an income of 1500 yuan per person so is willing to pay for improved cooking. Currently LNG costs about 30 yuan a month for cooking, honeycomb coal briquettes cost about 20 yuan and gas from the straw gasifier costs about 20 yuan/month.

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[Sun, L., 1995] et al, "Study of cropstraw gasification for village cooking gas", Proceedings of Asia-Pacific Regional Seminar on Technology for Utilization of Rice Husks and Other Agricultural Waste, 30-41, 1995.

5.12 *Sherbrooke, University of & Kemestrie Inc.*

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Process: Fluidized Bed Gasification of Wood and MSW

In November 1996 I visited the joint gasification research and development laboratories at Sherbrooke University and Kemestrie Inc. Sherbrooke University is relatively new and has strong ties to Canadian industry. The Kemestrie facilities are close by and are set up for commercialization of work performed at Sherbrooke under Prof. Chornet and colleagues. The gasifier and other operations at Kemistrie were explained to me by Dr. Nicola Abatzoglou. There are extensive research and analytical facilities at the University. A fluidized bed research facility is operating at Kemestrie Inc. Whereas most fluidized beds are focused on very large scale applications, the Sherbrooke/Kemestrie unit is seeking mid-size applications and has already found some (see below).

The fluidized bed PDU is modeled on the original Biosyn gasifier, but is very flexible and is available for testing various small scale fluid bed applications. The biomass consumption is < 10 tons/h.

The sand bed area is 30 cm internal diameter by 60 cm high (at rest). The gasifier is 4 m tall. The gasifier generates 100 sm^3/h of gas. The biomass enters through a small Sund feeder. 80% of the air enters through the grid of 8 tuyerres; 20% through the feed system. 5% of the heat transfer to the particles is by radiation, 95% by convection.

The gas exiting the gasifier passes through two cyclones and then through a wet scrubber. The installation is thoroughly instrumented for making a variety of measurements. The gasifier has been operated on wood shavings, mixed shavings and plastic, an RDF mixture, rubber residues and pure plastic. Two Ph.D theses and a patent application are to be completed in Spring 1997.

The intellectual property generated by Biosyn Inc. (see Biosyn) was transferred in 1989, by Nouveler, to the Centre Quebecois de Valorisation de la Biomasse (CQVB), a provincial corporation. The CQVB, under the leadership of M. Risi saw an opportunity to pursue gasification activities in the environmental area. Forest and agricultural residues, as well as MSW or RDF, and even industrial wastes, constitute low-cost feedstocks that were available worldwide in often small and localized sites. The CQVB launched a program to direct the technology towards small-scale environmentally-driven projects. It requested the participation of Sherbrooke University to prove that such an approach was technically, environmentally and economically sound. A research program thus started in 1990 at Sherbrooke University. It was led by E. Chornet . The program centered on the 50 kg/h gasifier that IREQ had build to carry out the research on behalf of Biosyn. The gasifier was transferred to Sherbrooke and a PDU facility built around the gasifier.

Since 1990, and with the support of federal and provincial agencies as well as private groups, Sherbrooke University has conducted a vigorous research program focusing on background research in support of the "small-scale gasification concept" identified as the market niche. In 1993, a spin-off company of Sherbrooke University, Kemestrie Inc., was formed to advance the commercialization of the biomass processes and products developed by the university researchers headed by E. Chornet. In 1995, a 100 kg/h unit aimed at recycling of aluminum from post-consumer packaging, was installed at a metallurgical plant in Que., Canada.

In 1996 an agreement was reached between Kemestrie Inc., led by P. Laborde and Biothermica Ltd., led by G. Drouin, to work together towards the commercialization of the Biosyn Technology which, besides the intellectual property generated in the 1990's, comprises the know-how and patents related to hot gas cleaning developed both by Kemestrie and Biothermica during the 1990's. The energy and environmental division of Kemestrie Inc., led by N. Abatzoglou, aims at the small capacity market (< 5 tons/h) whereas Biothermica centers its efforts in the larger capacity energy conversion market.

PROCESS SUMMARY

The aim of this process is the gasification of solid wastes for the production of a low heating value gas in a 50 kg/h (nominal) pilot scale fluidized bed gasifier [Jollez, 1991]. As of November 1990, three types of wastes had been gasified: wood (lignocellulosics); a mixture of wood (90% wt) and plastics (polyethylene/polypropylene, 10% wt); and a mixture of wood (85.5% wt), plastic/textiles (10% wt), compostable material (3% wt) and inorganic materials (1.5% wt) [Jollez, 1991]. The process is fully tested and ready for scale up to 1 ton/hour (March 1992). A scaled up version would provide low heating value gas to be used for the generation of electricity and/or process heat.

DESCRIPTION

Background

The University of Sherbrooke gasification plant located near Drummondville, Québec, Canada is a development of the Biosyn 10 ton/h pressurized (16 bar) fluidized bed gasification plant developed in the mid 1980's for the production of synthesis gas from lignocellulosic materials [Jollez, 1991]. The Biosyn gasifier was operated over a five year program and tests were conducted using a diesel engine fired using product gas. Approximately 680 hours experience was gained using the diesel engine fueled using producer gas. Prior to use in the diesel engine, the gas was scrubbed resulting in large volumes of dirty water. The Biosyn project was discontinued in 1988. Development of the University of Sherbrooke gasifier commenced in 1990 [Jollez, 1991]. Gasification tests were started in September 1990.

The 50kg/h gasifier used for the present research by the University of Sherbrooke was previously used as a support unit for the Biosyn project [Jollez, 1991]. Original funding was provided by the Centre Québécois de Valorisation de la Biomasse (CQVB), Distech Inc. and Canmet. Distech are a waste disposal company who wished to develop a 1 toni/hour gasification plant to convert MSW to low heating value gas for use in neighboring greenhouses. Distech are no longer involved with the project and the University of Sherbrooke now rent the building in which the gasifier is housed (from Distech). The University of Sherbrooke are currently negotiating with a waste disposal company in Sherbrooke to relocate the gasifier to Sherbrooke. The waste disposal company is nearer to the University of Sherbrooke, and will be able to provide a wide range of waste materials for test in the gasifier including waste rubber. Negotiations should have been completed by May 1992.

The aims of the research project started in 1990 were to [Jollez, 1991]:

- demonstrate that gasification is a viable option, both technologically and economically, for the conversion of wastes to energy;
- investigate the feasibility of high temperature reforming of tars and removal of undesirable gaseous contaminants (halogens and metal vapors);
- test high temperature filtration equipment;
- develop material and energy balances;
- determine eventual emissions as a function of feedstock;
- study the compatibility of the gas with either turbines or diesel engines;
- establish cost estimates for small and medium size units (1-10t/h) aimed at co-generation.

Existing Process

This section describes the 50kg/h pilot scale gasification plant near Drummondville, Québec. A diagram of the University of Sherbrooke gasification plant is shown in Figure 1 while actual process data is presented in Tables 1 (waste wood feedstock) and 2 (MSW feedstock). 80% of the reaction air enters the gasifier through the distribution plate at the base of the gasifier while the remainder enters through the feeding system to prevent back flow of gases from the reactor to the feed hopper [Jollez, 1991]. Air is provided by a forced draft fan.

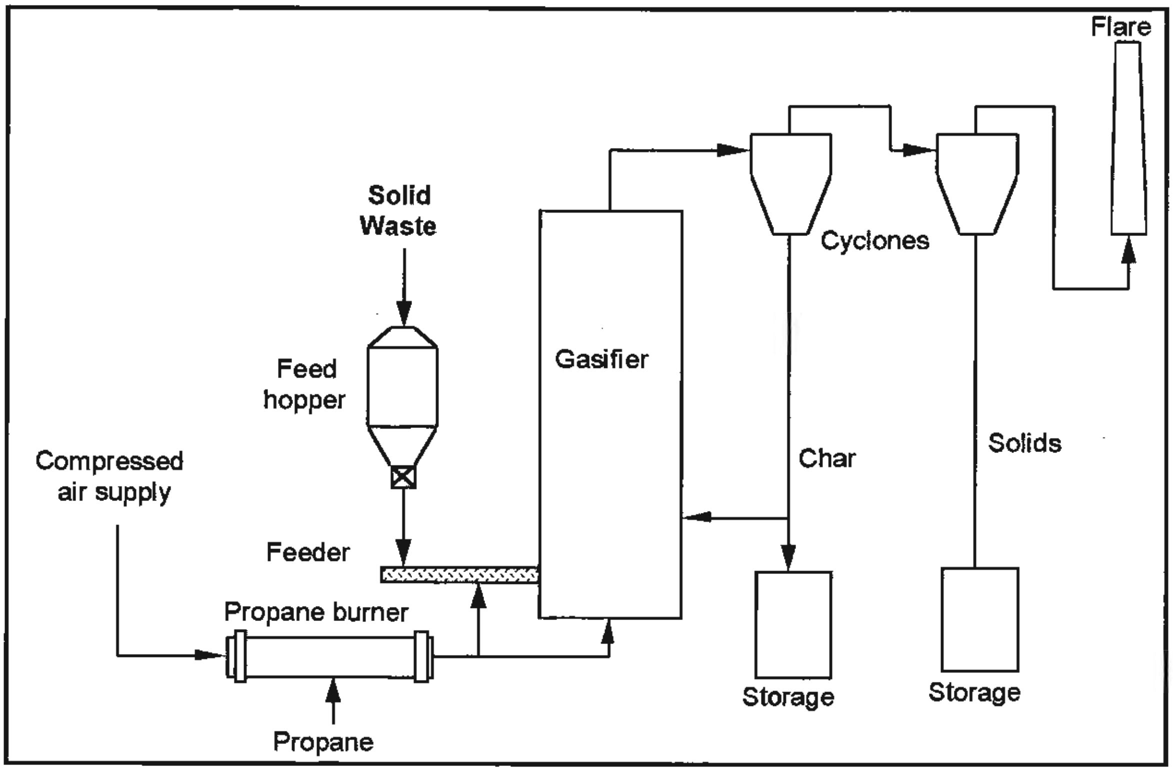

Figure 1 - University of Sherbrooke/CQVB/Distech/Canmet 50kg/h Fluidized Bed Gasifier [Jollez, 1991]

Startup takes approximately 20-30 minutes. Startup is carried out using a single propane burner which is used to heat inlet air to the gasifier distribution plate (see Figure 1). When the bed temperature has reached 400°C, feed is introduced to the bed which is burnt with excess air to raise the bed temperature to approximately 800°C. When the bed temperature is high enough, the equivalence ratio is adjusted to approximately 30% and operation commences.

The reactor is a bubbling bed fluidized bed gasifier with an internal diameter of 305mm. The highest bed height to diameter ratio tested has been 2 while the lowest has been 1. During the visit, the bed height was 45cm (bed height to diameter ratio of 1.5). The bed is made up of sand although it is intended to test the effect on product gas tar content of dolomite addition and the use of a bed composed of basic sand.

The equivalence ratio used is in the range 25-35%. Generally, it is aimed to operate with an equivalence ratio of 30%. During the visit, the equivalence ratio was 28%. This equivalence ratio is a little higher than that used in the SEI gasifier which operates at an equivalence ratio of approximately 25%. The higher equivalence ratio results in a lower gas tar content compared with the SEI gasifier.

The reactor incorporates no bed re-grading system. None has been found to be necessary. The bed pressure drop is continually monitored and if it increases to unacceptable levels, then the air flow rate is increased to blow any ash over into the cyclones for removal.

Table 1 - Existing Process Data from the Gasification of Wood [Jollez, 1991]

Process type	Gasification	
Main feedstocks tested	Residual wood	
Other feedstocks tested	mixed wood (90% wt)	& plastics (10% weight)
Main product	low heating value gas	
Main product yield	1.85	Nm^3/kg daf feed
Feedstock throughput (daf)	39.1	kg/h
Reactor type	Fluidized bed	
Primary reactor operating pressure	1	bar
Primary reactor operating temperature	700-800	°C
Reactant	air	
Reactant input rate	47.2	Nm^3/h
Equivalence ratio	27.3	%

Table 2 Existing Process Data from the Gasification of Glass and Metal Free MSW [Jollez, 1991]

Process type	Gasification	
Main feedstock	MSW fluff	
Main product	low heating value gas	
Main product yield	1.7-2.4	Nm^3/kg daf feed
Main product use	none in pilot	
Feedstock throughput (daf)	23.2-26.2	kg/h
Reactor type	Fluidized bed	
Primary reactor operating pressure	1	bar
Primary reactor operating temperature	700-800	°C
Reactant	air	
Equivalence ratio	24.3-32.2	%
Liquid waste flow rate (tars)	0.03-0.04	kg/kg daf feed
Solid waste flow rate (char)	0.01-0.03	kg/kg daf feed

Following the gasifier, two cyclones are used to remove any solids in the gas (see Figure 1) [Jollez, 1991]. Char from the first cyclone can be re-injected into the top of the fluidized bed (at the same level as the upper feed point). Little work has been carried out, however, investigating char recycle. In addition, the char recycle pipe diameter is considered to be too small. During operation, the char from the cyclones is discharged into storage bins for later disposal.

Planned Modification, Developments, Extensions

A laboratory research project has been started to investigate the catalytic cracking of tars in the product gas using a fixed bed reactor [Jollez, 1991]. Following completion of the laboratory research, a sand filter and catalytic cracker will be fitted on to the pilot plant downstream of the two existing cyclones. The catalytic cracker will process only 20% of the total product gas from the gasifier to enable an assessment of the cracker efficiency to be made.

FEEDSTOCKS AND CHARACTERISATION

Three full test programs have been carried out using three types of feeds. The compositions of the three feedstocks are shown in Table 3. Feed A consists of waste wood (sawdust) while feed B consists of sawdust plus added plastics. Feed C consists of sorted and shredded MSW (mainly paper and card). Full output can be obtained using the waste wood feed. As noted above, feeding problems restricted the gasifier performance when operating using MSW.

Table 3 - Feedstock Compositions [Jollez, 1991]

	Feed A %weight	Feed B % weight	Feed C % weight
Lignocellulosics	100	90	72.5
Plastics	0	10*	10#
Compostable material	0	0	3
Inorganic materials (glass, metal)	0	0	1.5

*** Includes polyethylene and polypropylene # includes textiles**

The feeds are ground and shredded to a characteristic dimension of less than 1cm. During the visit, the gasifier was operating using sawdust (<2mm). The average wood (feed A) moisture content is 12% while the shredded MSW fluff (feed C) had a moisture content of approximately 20%. Feedstock preparation is reported to be essential to ensure uniform feeding rates and product gas composition [Jollez, 1991].

PRODUCTS

Gas Characteristics

The product of this process is a low heating value gas which has a higher heating value (carbon, tar and moisture free) of 6.1 MJ/Nm^3 corresponding to approximately 13.8 MJ/kg dry feed [Jollez, 1991]. Table 4 shows actual gas compositions and characteristics of gases produced using the three feeds tested (see Table 3).

The gas produced (from MSW) requires treatment prior to use in an engine because it contains fine residual carbon (approximately 1.5% by mass of dry MSW) and tar (between 2.8 and 3.8% by mass of dry MSW) [Jollez, 1991]. Investigations are underway to study catalytic cracking of tars using a fixed bed reactor (see Section 2.2.2) [Jollez, 1991].

Liquid Products Characteristics

Tar is produced during the gasification process, considered as a waste product (see Section 6.2.1).

Solid Products Characteristics

A solid char is produced during the gasification process which is considered a waste material (see Section 6.3.1).

PERFORMANCE

A process flow diagram based on the results using MSW as feedstock has been developed [Jollez, 1991]. A mass and energy balance for the gasification of 1 toni/h of MSW based on the results obtained from the gasification tests completed using the 50 kg/h pilot plant is shown in Table 5.

Table 4 - Summary of Actual Gas Characteristics [Jollez, 1991]

	Feed A	Feed B	Feed C	Units
Dry gas composition volume	%	%	%	
Hydrogen	9.8	8.2	5.3	
Carbon monoxide	15.8	11.4	12.1	
Carbon dioxide	16.1	16.8	15.6	
Methane	6.1	6.2	2.6	
C_2+	nr	nr	4.5	
Oxygen	0.8	0.8	1.1	
Nitrogen	51.5	56.8	53.7	
Gas output rate (dry)	89.5	58.8	19.5	kg/h
Gas exit temperature from system	780	nr*	740	°C
Higher heating value (dry gas)	6.2	5.8	6.1	MJ/Nm^3

* nr - not reported

The experimentally determined product gas yield from the gasification of wood is approximately 2.3 kg/kg daf feed while the yield of gas from the gasification of MSW is approximately 2.6 kg/kg dry feed.

EMISSIONS

Gas

This process produces no gaseous emissions as all gases from the system form the product.

Liquid Emissions

The gas produced contains between 2.8 and 3.8 % mass dry MSW feed of tar [Jollez, 1991].

Pollution Control Technologies

Investigations are being carried out to study the catalytic reforming of tars (studied using napthalene as a model compound) at similar temperatures to the gas exit temperature from the fluidized bed gasifier [Jollez, 1991].

Table 5 - Mass and Energy Balances over Gasifier [Jollez, 1991]

Mass balance Energy balance	kg	MJ
Inputs: Basis - 1000 kg MSW feed		
MSW	1000	14800
Air	1517	0
Outputs		
Hot gas	2432	12563
Char	85	2237
Closures, %	100	100
Gas cooling		
Basis: 1000 kg MSW feed	Inputs	Outputs
Hot gas	2432	12563
Condensate	338	3473
Cold gas	2094	9090
Closures, %	100	100
Hot gas efficiency, %	84.9	
Cold gas efficiency, %	61.4	

Solid

Solid Emissions

The gas produced contains approximately 1.5% (by mass dry feed) of fine residual carbon [Jollez, 1991].

Pollution Control Technologies

The product gas is passed through two cyclones prior to use to remove any particulates (see Figure 1). The collection efficiency of the cyclones is considered to be low (efficiency not reported). Further particulate removal would be required if the gas were to be used to fuel and engine.

PROCESS COSTS

Economic estimates for small to medium size gasification units (1 toni MSW/hour) for the production of electricity and process heat have been performed (see Table 5) [Jollez, 1991].

Capital Costs

From the material and energy balances shown in Table 5, cost estimates for a prototype cogeneration installation treating 1 toni/hour of MSW have been performed [Jollez, 1991]. The cost estimates have been carried out for a gasification scheme which includes gas cooling, scrubbing and filtration equipment (filtration/reforming equipment is not as yet available) for the production of electricity using an engine [Jollez, 1991]. One toni of MSW (dry basis) is estimated to generate 0.76 MWh (electrical) and a minimum of 3300 MJ available as hot water or steam [Jollez, 1991]. The use of hot gas cleaning/reforming will double the amount of process heat available [Jollez, 1991].

The total capital cost (November 1991) of a 1 toni MSW/h throughput cogeneration scheme is estimated to be US$1.9 million (Can$2.25 million) [Jollez, 1991].

Operating Costs

Working capital costs of US$211 000 (Can$250 000) are estimated for a 1 toni MSW/h plant (November 1991) [Jollez, 1991].

Product or Production Costs

Estimates for the production cost of electricity from a 1 toni MSW/h plant are reported assuming that the entire investment is financed through borrowing at interest rates between 10 and 14% [Jollez, 1991]. The results show the required MSW tipping fee as a function of the electricity price (Figure 2). The two cases shown correspond to process heat production produced using the hot gases from the proposed process displacing either No. 6 fuel oil or natural gas [Jollez, 1991]. It can be seen that at an annual interest rate of 12% and if oil has been replaced as fuel for the production of process heat then a MSW tipping fee of Can$34/tonne (US$28.70) needs to be collected by the utility to make the process economically self supporting [Jollez, 1991].

Markets for Product

The gaseous product can be used for direct firing for hot water or steam production or for the generation of electricity.

CURRENT STATUS AND FUTURE PLANS

The 50kg/h pilot scale gasification plant is part of a two phase programme investigating the gasification of waste materials [Jollez, 1991]. In the second phase of the programme, the prototype plant will be scaled up to1 ton/h based on the process parameters and configurations developed during the pilot plant phase [Jollez, 1991]. The system is currently ready for scale-up to 1 toni/hour at one barg pressure. However, as Distech is no longer involved in the project, the scale-up phase of the project is currently suspended until a partner is found. There is reported to be little interest in biomass gasification in Canada although there is interest in waste gasification.

The license for the gasification plant is held by CQVB. If a UK company wanted to build a similar gasifier, CQVB would license the technology and appoint the University of Sherbrooke or an affiliated technology transfer company as Engineering assistants. The University of Sherbrooke would provide full cooperation.

5.13 *Tata Energy Research Institute - Wood-Gas System For Silk Production (Tata, SDC, IDC,TERI)*

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India produces 15,000 tons of silk a year and is the second largest silk producing country (after China). Sericulture requires large quantities of wood which are used wastefully in this industry for stifling (killing the pupae), cooking (to remove gums), reeling, re-reeling and degumming and dyeing, all in boiling water. There are 60,000 ovens being used by half a million people, mostly women. It is estimated that 475,000 tons/yr of wood, (Tamarind, Neem, sawmill waste) as well as rice husk, peanut shells and leaves are consumed in these processes.

A number of non-government organizations (NGOs) are interested in developing small gasifiers to aid in the silk industries. These include the SDC (Swiss Development Corporation), IDE, (International Devilment Enterprises), (?)(?) . They expect that use of gasification would

- reduce fuel consumption by more than a factor of 2
- increase thermal efficiency from 10% to 50%
- give better process control
- reduce smoke and provide better working conditions and possibly better productivity
- permit the clean flue gases to be used for drying pupae
- use the gas for stifling cocoons rather than boiling

On October 23 I was taken by V. V. Kishore of the SDC in Delhi to visit an experimental test farm. I saw an experimental gasifier designed by a SDC team being tested for efficiency in silk processing. It is thought that the conventional cooking is less than 10% efficient (logs under 6 boiling pots) and that the gasifier will be closer to 40% efficient as well as much more controllable and less polluting.

The gasifier used was a simple stratified downdraft with a closed fuel magazine as shown in Fig. 3.(?). The gas was forced by a blower through the gasifier, and then through a horizontal scrub unit and fed to the six burners under six copper pots in a cooking table. Workers dumped fresh cocoons into the boiling water and removed a sludge of loose fibers and gum that was allowed to dry and sold as feed. Reeled sild yarn is soldin the market.

Figure 1 - SDC Gasifier for Silk Processing. Gasifier supplies adjustable heat to each of 6 vats, greatly increasing silk production and reducing wood consumption a factor or 2

Currently the gasifiers are estimated to cost 40,000 Ru, possibly 35,000 Ru with large scale production. It was also my impression that the cost could be lowered by making a tar free gas and dispensing with the filter system, but this would require further development (see below).

On October 26 I was driven from Bangalore to Ramanagaram with S. N. Srinivas (anu@ampersand.soft.net) to look at these gasifiers in operation at two silk factories. Each mill employed a dozen workers, mostly women (and seemed to provide day care and some child labor therefore.) The gasifier took a few minutes to start and then the burners were lighted under the cooking pots and operated for many hours. It is estimated that each burner uses 2.5 kWth, so the gasifier operates at about 15 kWth and requires 7-8 kg wood per hour. A worker occasionally would cut up wood into chunks 5 cm in maximum dimension using a simple circular saw/motor rig and dump them into the gasifier hopper. The manager of the mill said that the output of silk was increased 2-4% by the use of the gasifiers. The workers were enthusiastic about the new tool.

I believe that it might be possible to eliminate water scrubbing altogether and reduce the price (and dirty water output) significantly if low tar operation were incorporated in the process. Finally, one issue that needs careful consideration is the use of "suction" Vs "pressurized" gasifiers for the silk industry. Engine gasifiers are normally suction because the engine suction is used to pull air/gas through the system to the engine. But an added advantage is that any small leaks will take air in – not leak carbon monoxide out. The TERI gasifiers use a blower to force air through the system, so any leaks will be a potential source of CO. A CO alarm should certainly be part of any installation.

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5.14 *VTT Gasification R&D Center*

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Purpose:	R&D on gasification, gas cleanup, power

VTT is the Technical Research Center of Finland and their main energy laboratories are located in Espoo, suburban Helsinki. In September 1996 they hosted a joint workshop of the European Union, EU, Concerted Action "Analysis and Coordination of the Activities Concerning Gasification of Biomass" and the International Energy Agency, IEA working group "Biomass gasification". The workshop was at the Hotel Hanasaari, a conference center on the Gulf of Finland, West of Helsinki. I attended this workshop as a guest and met many of the major players in the field and heard their presentations. I have used the Minutes of this meeting as a major source of technical information on project reports on large scale gasification [Kaltschmitt, 1996].

Table 1 - Gasification test facilities at VTT Energy

	PDU/PRU GASIFIERS	
Pressurized fluidized bed gasification test rig (1988-)	• Up to 80 kg/h feed rate • Pressure 3-10 bar • temperature 700-1100°C	• Tests with new feedstocks for IGCC applications • Gas filtration tests • By-pass testing of secondary gas cleaning catalysts
Circulating FB gasifier (1995-)	• Up to 50 kg/h feed rate • atmospheric pressure • temperature 700-1100°C	• tests with waste materials and biofuels for atmospheric pressure applications • Development of gas cleaning for CFB gasifiers
Fixed-bed gasifier and thermal cracker (1985-)	• up to 25 kg/h feed rate • atmospheric pressure	• Tests with waste materials
	BENCH SCALE RIGS	
Pressurized fluid-bed reactor for fundamental studies (1993-)	• batch/continuous feed • id 30 mm, SiC-reactor • pressure 1.2-20 bar	• fluid-bed pyrolysis tests • reactivity tests • gas cleaning studies
Fluid-bed reactor and Cracking unit (1995-)	• gasifier, filter, res time tub • continuous feed, 1 kg/h • bar, max 1,000°C	• pyrolysis in N_2 • preliminary air gasification tests with new feedstocks
Filter testing facility (1993-)	• synthetic gas, 1-5 bar • temperature 300-900°C	• fate of tars and soot • corrosion of filter materials • filtration tests
Fluid-bed reactor for ash sintering studies (1995-)	• 1 bar, up to 1100°C	• Sintering tests in real fluidized-bed conditions
Pressurized monolith catalyst reactor (1994-)	• up to 10 bar, 1000°C • syn gas or real gasification gas from PDU gasifier	• catalytic decomposition of tars and NH3 • other gas cleaning tests
Entrained flow reactor (1995-)	• 1 bar, up to 1400°C • air, N_2, or syn gas atmosphere • feed rate up to 1 kg/h	• fundamental studies on formation of gas contaminants • fuel characterization

VTT has been carrying out projects on biomass and peat gasification since the late 1970s. In the early 1980s, the research comprised simple atmospheric pressure fuel gas applications including a gasification heating plant, lime kilns and other close coupled applications where no gas cleaning was required. This development culminated in the commercialization of the Bioneer fixed-bed gasifier. In 1986-1995 the work has focused on the development of simplified IGCC power systems based on pressurized fluid-bed gasification and hot gas cleaning. This research has been carried out in close cooperation with the Finnish industry and European utility companies. Recently VTT also restarted activities in atmospheric-pressure gasification of biomass for engine applications and for co-firing of biomass derived gas in large utility boilers. In addition to publicly funded research, VTT test rigs are used for privately funded R&D projects of Finnish and European industries [Moilanen, A , 1996, 1996b].On September 29 we went on a field trip to the VTT laboratories in Espoo. We saw a number of their test rigs, asked questions about preferred catalysts and were all impressed by the level of expertise and long experience they have in this field. Table 3.(?) summarizes their facilities **which are the most comprehensive gasification and gas cleanup testing facilities in the world.**

LABORATORY FACILITIES

- Ambient pressure and pressurized TGA-facilities
- Pressurized-heated grid apparatus
- pyroprobe pyolysis-GC (AED/MS)
- Tube reactor for studies oon gas phase reactions
- Pressurized fixed bed reactor for catalyst and fuel testing
- portable fixed-bed test rig for catalyst testing (1 bar)

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5.15 *Wales, University of*

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The Department of Mechanical Engineering and Energy Studies of Cardiff University of Wales has been working in the field of gasification under Prof. N. Syred. Dr. David Beedie has completed his thesis on "Characterisation and Control of a Batch-Loaded Biomass Gasifier-Combustor". He carried out research to analyze and improve the operation of a manually-loaded biomass-fired air-heating unit. The 200 kWth fixed-bed system with integral gas-air heat exchanger was designed and constructed for an EC-funded project carried out jointly between Cardiff University and the Universiti Teknologi of Malaysia. The system used agricultural crop wastes for clean crop-drying. The complete results are to be found in the thesis.

5.16 *ZARAGOZA UNIVERSITY*

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The biomass research team at the University of Zaragoza and other partners are involved in the Joule project "Hybrid Wind-Biomass system for rural electricity generation". The global objectiveof this project is to develop a system to provide electricity for rural locations without the use of any form of fossil fuel. The University of Zaragoza is working on the design and construction of a 50 kg/h downdraft air gasifier.

In the gasifier air is fed radially by three tuyeres. THe bed is supported on an eccentric rotating grate in the bottomof the gasifier and an agitation system prevents voidage formation in the bed. A novel feature is that the gasifier can operate in an "idle" mode, ticking over. When power is required the gasifier starts immediately.

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CHAPTER 6 - CONVERSION FACTORS

The U. S. has been dragging its feet on conversion to metric and continues to use the ENGLISH system even after the English have given it up (at least officially). The metric system makes many calculations trivial - after you learn it. Personally, I have used metric as a scientist and English for engineering, but on my world trip I had to "speak metric" so much that I am now 90% converted to SI.

WEIGHT: 1 kg = 2.204 lb = 0.984 X 10^{-3} ton (long) - 1.1023 X 10^{-3} ton (short)

PRESSURE: 1 atm = 1.0133 bar = 101.33 kPa = 14.7 psia = 29.921 in. Hg = 1419 in. H_2O = 760 mm Hg

VELOCITY: 1 m/s = 3.281 ft/s = 3.6 km/h = 2.237 mph

ENERGY: 1 Btu = 1.055 kJ = 252 Cal = 778.2 foot-pound-force

1 kWh = 3.600 MJ = 3413 Btu

1 Cal = 4.187 J

DENSITY: 1 g/cm^3 = 1000 kg/m^3 = 62.43 lb/ft^3

1 lb/ft^3 = 0.01602 g/cm^3 = 16.02 kg/m3

POWER: 1 watt = 1 J/s = 3.43 Btu/h = 0.2389 Cal/s = 3.6 kJ/h = 1.341 X 10^{-3} hp

TEMPERATURE: °F = 1.8°C + 32 °C = (°F-32)/1.8 °K = °C + 273.15

°R= °F + 450.67 = 1.80 °K

LENGTH: 1 in = 2.54 cm 1 micron (micrometer) = 1 μm = 10^{-6}m

VOLUME COMPRESSIBLE GAS:

1 Nm^3 (0°C) = 35.315 ft^3 (32°F) = 38.55 scf (77°F) = 37.32 scf (60°F)

VOLUME NONCOMPRESSIBLE:

1 m3 = 35.315 ft^3 = 1000 liters

1 ft^3 = 0.02831 m3 = 7.48 gal

1 gal (US) = 3.785 liters = 0.1336 ft^3 = 231 in^3

GAS FLOW: 1 Nm^3/h = 0.632 scfm (68°F)

AREA: 1 m^2 = 10.76 ft^2 = 1550 in^2 = 1.30 yd^2

HEARTH LOAD (for 130 Btu/scf Gas):

0.9 Nm^3/h-cm^2 = 5.37 scfm/ft^2 = 3.73 scfm/in^2 = 4.2 Mbtu/h-ft^3

GAS ENERGY CONTENT:

1 Btu/scf (68°F) = 9.549 kCal/Nm^3 (0°C) = 40.0 kJ/Nm^3 (0°C) = 0.040 MJ/Nm^3

FUEL ENERGY: 1 Btu/lb = 0.5555 Cal/g = 2.326J/g 1 Cal/g = 1.8 Btu/lb = 4.187 J/g

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GASIFICATION RULES OF THUMB - APPROXIMATELY TRUE - & EASY TO REMEMBER

1 kg biomass (10%MC) ≈ 18MJ

1 kg yields 5 kWh (thermal)

1 kg yields 1 kWh (electric) when converted with 20% efficiency

1 m^3 of producer gas weighs 1 kg

1 kg biomass combines with 1.5 kg air to give 2.5 kg producer gas = 2.5 m3 (if gasification air/fuel ratio = 1.5)

1 ppm tar in 1 m^3 gas weighs 1 mg
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CHAPTER 7 - GLOSSARY

As explained in the text, the meanings of words IS important and misunderstandings can wreak havoc in a field. We have given our definition of some of the words used here (but don't argue with others using the words differently.

The field of gasification is full of acronyms. We will try to spell them out the first time we use them, but after that they are very useful - and annoying for someone browsing the text. So we spell them out here again.

BFB: Bubbling fluid bed

BIOMASS: Usually lignocellulosic materials (wood, straw,...) being considered as a source of energy, but also municipal solid waste, vegetable oils, recycled materials etc. discussed in relation to their energy use. (Phytomass is vegetable in origin; zoomass is animal in origin.)

CFB: Circulating fluid bed

CHAR/ASH: Charcoal remaining after gasification, containing 20-90% ash.

CHARCOAL: Solid fuel from biomass pyrolysis containing varying amounts of carbon and smaller amounts of volatiles produced, depending on the final temperature reached. There are many grades of charcoal (see Xcoal).

COMBUSTION: Reaction of fuels with air/oxygen to produce primarily CO2 and H2O.

DOE The U.S. Department of Energy

EPA The U.S. Environmental Protection Agency

FB: Fluidized bed

FLAMING COMBUSTION: Pyrolysis in the presence of sufficient air for total combustion, producing primarily CO2 and H2O, as in a match.

FLAMING PYROLYSIS: Pyrolysis in the presence of insufficient air for full combustion, producing significant quantities of CO and H2 and smaller amounts of volatiles.

GASIFICATION: Conversion of solids to gas by pyrolysis or air/oxygen

GLOWING COMBUSTION: Reaction of a solid, typically carbon, coal or coke, with air very close to or at the surface of the solid so that the solid is luminous (glows) as in a barbecue (after ½ hour) or blacksmith's forge.

IGCC: Integrated gasifier-combined cycle power generation

MSW Municipal solid waste, usually in relation to energy production

MWe Electric power in MW

MWth	Heat power in MW
PDU	Process development unit
PYROLYSIS:	The breakdown of materials (lysis) with heat (pyro). Strictly speaking in the absence of air, but the heat supply is often aided by combustion nearby.
THERMOLYSIS:	Controlled pyrolysis in which total breakdown is avoided (as in cooking).
X-Coal:	A more precise word for charcoal (still waiting to be defined), where X is the degree of volatile removal, the fraction of hydrogen and oxygen remaining or the fraction of water removed.

CHAPTER 8 - REFERENCES

The following are general references included as recommended reading and specific references called out in the text from the various chapters. In addition a list of biomass gasification "Books in Print" from the Biomass Energy Foundation Press are found at the end of this section. References are also included for convenience in some of the chapters.

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