

# **GASIFICATION FOR DISTRIBUTED GENERATION – TASK 3.5**

Final Topical Report

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## TABLE OF CONTENTS

LIST OF FIGURES .....	ii
LIST OF TABLES .....	ii
EXECUTIVE SUMMARY .....	iii
INTRODUCTION .....	1
STATEMENT OF WORK .....	2
OBJECTIVES .....	3
EXPERIMENTAL .....	3
Feedstock .....	3
Black Liquor .....	3
Alfalfa .....	4
Willow (Salix) .....	4
Manure .....	4
Gasification – TGA .....	4
Gasification – IBG .....	5
Product Analysis .....	5
RESULTS AND DISCUSSION .....	6
CONCLUSIONS .....	14
RECOMMENDATIONS .....	15
REFERENCES .....	15
GASIFICATION FOR DISTRIBUTED GENERATION: A MARKET SURVEY .....	APPENDIX A

## LIST OF FIGURES

1 Hydrogen production from biomass at several temperatures . . . . .	9
2 Carbon dioxide production from biomass at several temperatures . . . . .	9
3 Carbon monoxide production from biomass at several temperatures . . . . .	10
4 IR chromatogram of methane production from gasification of black liquor, alfalfa, and willow . . . . .	11
5 IR chromatogram of carbon dioxide production from gasification of black liquor, alfalfa, and willow . . . . .	11
6 IR chromatogram of carbon monoxide production from gasification of black liquor, alfalfa, and willow . . . . .	12
7 IR chromatogram of sulfur dioxide production from gasification of black liquor, alfalfa, and willow . . . . .	12
8 IR chromatogram of nitrogen dioxide production from gasification of black liquor, alfalfa, and willow . . . . .	13

## LIST OF TABLES

1 Plan . . . . .	1
2 Biomass Gasification Feedstocks . . . . .	4
3 Proximate/Ulimate Analysis Results . . . . .	6
4 Reactivities and Arrhenius Energy of Activation ( $E_a$ ) for Steam-Gasified Biomass . . . . .	7
5 Gasification Products by Phase (MF) . . . . .	7
6 Column Chromatographic Separation of Tars . . . . .	8
7 XRF Analysis of Black Liquor Ash at Two Temperatures . . . . .	13

## GASIFICATION FOR DISTRIBUTED GENERATION – TASK 3.5

### EXECUTIVE SUMMARY

A recent emphasis in gasification technology development has been directed toward reduced-scale gasifier systems for distributed generation at remote sites. The domestic distributed power generation market over the next decade is expected to be 5–6 gigawatts per year. The global increase is expected at 20 gigawatts over the next decade. The economics of gasification for distributed power generation are significantly improved when fuel transport is minimized. Until recently, gasification technology has been synonymous with coal conversion. Presently, however, interest centers on providing clean-burning fuel to remote sites that are not necessarily near coal supplies but have sufficient alternative carbonaceous material to feed a small gasifier. Gasifiers up to 50 MW are of current interest, with emphasis on those of 5-MW generating capacity. Internal combustion engines offer a more robust system for utilizing the fuel gas, while fuel cells and microturbines offer higher electric conversion efficiencies. The initial focus of this multiyear effort was on internal combustion engines and microturbines as more realistic near-term options for distributed generation.

In this project, we studied emerging gasification technologies that can provide gas from regionally available feedstock as fuel to power generators under 30 MW in a distributed generation setting. Larger-scale gasification, primarily coal-fed, has been used commercially for more than 50 years to produce clean synthesis gas for the refining, chemical, and power industries. Commercial-scale gasification activities are under way at 113 sites in 22 countries in North and South America, Europe, Asia, Africa, and Australia, according to the Gasification Technologies Council.

Gasification studies were carried out on alfalfa, black liquor (a high-sodium waste from the pulp industry), cow manure, and willow on the laboratory scale and on alfalfa, black liquor, and willow on the bench scale. Initial parametric tests evaluated through reactivity and product composition were carried out on thermogravimetric analysis (TGA) equipment. These tests were evaluated and then followed by bench-scale studies at 1123 K using an integrated bench-scale fluidized-bed gasifier (IBG) which can be operated in the semicontinuous batch mode.

Products from tests were solid (ash), liquid (tar), and gas. Tar was separated on an open chromatographic column. Analysis of the gas product was carried out using on-line Fourier transform infrared spectroscopy (FT-IR). For selected tests, gas was collected periodically and analyzed using a refinery gas analyzer GC (gas chromatograph). The solid product was not extensively analyzed.

TGA tests were carried out at atmospheric pressure in excess steam over the temperature range 973–1073 K (1292°–1472°F). The preexponential (frequency) factors over this temperature range for alfalfa, black liquor, manure, and willow were  $1.6 \times 10^{12}$ ,  $6.3 \times 10^{13}$ ,  $4.2 \times 10^{18}$ , and  $3.7 \times 10^{20}$ , respectively, and the reactivities were 20.1, 36.7, 43.6, and 48.9 kcal/mol°C, respectively. The reactivity of willow became similar to that of black liquor and manure at 1123 K.

Three of the four feedstocks, i.e., black liquor, alfalfa, and willow, were gasified in the IBG. Gasification products from three biomass feeds were partitioned into three phases: solid residue, most of which was found in the reactor as ash but a small amount was deposited in the piping leading to the condensers; liquid organic portion (tar) which condensed in the piping and condensers; and moisture-free gas, which was determined by difference. The solids and water condensate, in which the sodium from the black liquor is expected to be found, were not analyzed as part of this study. Tar was partially characterized by separating it into alkane, waxes, aromatics, and polar fractions using a specially developed technique referred to locally as "short column chromatography," which is an application of activated silica gel open column chromatography. Black liquor produced approximately one-half the tar of the other two feeds, probably due to the tar-cracking properties of the alkali metal (sodium), but nearly 3 times as much aromatic material per gram of tar. The synthesis gas produced during the reactions was rich in hydrogen. In accordance with classical kinetics, as the temperature of the reaction increased, so did the reaction rate as indicated by the reactivities. H<sub>2</sub> production increased as temperature increased, as did CO<sub>2</sub> except, as explained by water-gas shift, at the highest temperature for the black liquor and willow gasification.

This report is a part of a search into emerging gasification technologies that can provide power under 30 MW in a distributed generation setting. Larger-scale gasification has been used commercially for more than 50 years to produce clean synthesis gas for the refining, chemical, and power industries, and it is probable that scaled-down applications for use in remote areas will become viable. The appendix to this report contains a list, description, and sources of currently available gasification technologies that could be or are being commercially applied for distributed generation. This list was gathered from current sources and provides information about the supplier, the relative size range, and the status of the technology.

## GASIFICATION FOR DISTRIBUTED GENERATION – TASK 3.5

### INTRODUCTION

The Energy & Environmental Research Center (EERC) at the University of North Dakota has more than 20 years of experience in gasification research at the laboratory, bench, and pilot scale. Background includes experience in gasification of fossil material, including coal, peat, and petcoke; synthetic waste material such as ebonite and other plastics; and, more recently, biomass such as natural and hybrid poplar (genus *Populus*) and willow trees (genus *Salix*), sunflower seed hulls, and common cattail (*Typhus augustofolia*) (1–27). Tests results have included operational and environmental data pertinent to large-scale gasifiers such as the Dakota Gasification Plant in Beulah, North Dakota, and data have been obtained for both fixed-bed and fluidized-bed gasifiers.

A recent emphasis in gasification technology development has been directed toward reduced-scale gasifier systems for distributed generation at remote sites. The economics of gasification for distributed power generation are significantly improved when fuel transport is minimized. Until recently, gasification technology has been synonymous with coal conversion. Presently, however, interest centers on providing clean-burning fuel to remote sites that are not necessarily near coal supplies but have sufficient alternative carbonaceous material to feed a small gasifier. As with siting coal utilization plants at the minemouth, building the facility near the feed source increases the attractiveness of converting solid or semisolid feedstock to gas. In addition, gasification offers the advantage of removing potential pollutants from the fuel stream prior to combustion. Gasifiers up to 50 MW are of current interest, with emphasis on those of 5-MW generating capacity. Internal combustion engines offer a more robust system for utilizing the fuel gas, while fuel cells and microturbines offer higher electric conversion efficiencies. The initial focus will be on internal combustion engines and microturbines as more realistic near-term options for distributed generation. Several issues with regard to reduced-scale commercial gasification need to be addressed in evaluating the feasibility of the technology. Table 1 outlines the approach to addressing these issues in a multiyear program.

TABLE 1

Plan			
Approach	Activity	Issue Addressed	Year of Activity
Literature Review	Collect and collate data. Establish conditions for scoping tests. Survey available equipment	Char reactivity Solids handling	Year 1
Thermogravimetric Analysis/Bench-Scale Gasifier/Differential Thermal Analysis	Scoping/exploratory tests	Char reactivity Tar cracking Fuel choice/characterization Sintering	Year 1

Distributed generation typically applies to relatively small power generation technologies typically under 30 MWe that produce power at or near the end users. When a power plant is located close to the consumer, the technology can usually support the economics of the existing distribution grid and provide higher reliability of service and higher efficiency by utilization of waste heat.

In this project, we are looking at emerging gasification technologies that can provide power under 30 MW in a distributed generation setting. Larger-scale gasification has been used commercially for more than 50 years to produce clean synthesis gas for the refining, chemical, and power industries. Commercial-scale gasification activities are under way at 113 sites in 22 countries in North and South America, Europe, Asia, Africa, and Australia, according to the Gasification Technologies Council (28).

Two major experiential areas provide the backbone experience in commercial gasification. This includes experience gathered from past town gas systems, when the economics favored distributed synthesis gas from coal to provide lighting and heat, and current major commercial projects supporting refining, chemical, and power industries. The majority of these commercial gasification projects are fired with coal and petroleum in which 11.1 billion standard cubic feet of gas per day are produced, equivalent to 535,000 barrels of oil. Between 1996 and 1998, power production from gasification has seen a 22% increase. When the overall gasification market is assessed, coal accounts for 40% of the feedstock being used, and power makes up 26% of the final product. The majority shares are petroleum at 49% and chemicals at 51%, respectively. The major players in this market include Shell, Lurgi, Prenflo, Carbona, Texaco, Destec, and KRW. Of these companies, the majority are focused on large-capacity systems, which economies of scale would favor. Only a few of these companies have smaller systems available for distributed generation.

The market drivers for distributed generation and gasification in general include the growing distributed generation market and opportunity fuels such as biomass. What is causing the distributed generation market to grow is the increasing demand for electricity, gains in small modular power generation technologies, environmental concerns, and reliability or backup power. Gasification is likely to become a share of this market because opportunity fuels such as biomass can potentially be used in combination with IC (internal combustion) engines, innovative steam engines, gas turbines, microturbines, fuel cells, and Stirling engines. The domestic distributed power generation market over the next decade is expected to be 5–6 gigawatts per year (29). The global increase is expected at 20 gigawatts over the next decade.

## **STATEMENT OF WORK**

This subtask evaluated some of the major parameters important to optimizing the design of a small-scale gasifier for distributed power generation. A literature survey providing data and information for comparison with data obtained from laboratory- and bench-scale testing was obtained. Physical and chemical characteristics of feed and products, char reactivity, tar characteristics, products of tar cracking, and gas composition were determined. Proximate/

ultimate analyses, thermogravimetric analyses (TGA), ash analysis, column chromatography, gas chromatography, and infrared spectrometry were used for characterization of the product streams. Gasification tests were performed on the laboratory and bench scale during this program year. Approaches to generate a gas quality suitable for both IC engines and microturbines were evaluated during the initial scoping/exploratory tests. Results from these tests will be utilized to plan tests in Year 2 to obtain optimize data for designing a small-scale gasifier.

## **OBJECTIVES**

The overall objective is to obtain laboratory and marketing information necessary to develop designs for a small-scale electrical generating station for use with local fuel supplies at remote locations. Specific objectives are as follows:

- Collect and collate data on reactivity of char under uncatalyzed and catalyzed gasification conditions.
- Survey literature for available equipment for solids handling.
- Characterize gasification feedstock.
- Determine reactivities of candidate gasification feedstock.
- Determine the effect of catalyst on gasification tar cracking.

## **EXPERIMENTAL**

### **Feedstock**

The feedstock characteristics used in this gasification study are described below and are summarized in Table 2.

#### ***Black Liquor***

The black liquor used in this study was a waste product from treatment of barkless Aspen hardwood in producing paper pulp. The liquor was heavy, viscous black liquid that poured slowly from the container. Effervescence occurred on adding HCl to the liquor. When heated, the liquor expanded severalfold. A portion of the liquor was heated to 400 °C to produce a “devolatilized” black liquor. Since large amounts of sodium are used in the pulping process, an acid extraction was carried out on a portion of the devolatilized black liquor to remove residual sodium from the liquor. Following acid extraction and drying, the material still expanded when heated.

TABLE 2

### Biomass Gasification Feedstocks

Feed	Willow	Willow	Alfalfa	Manure	Black Liquor
Source	SUNY–NY	USDA–WI	Granite Falls–MN	Cattle Ranch–ND	Paper Mill–MN
Received Form	Sticks	Sticks	Dried plant	Weathered pie	Raw liquor
Received Size	¼–1¼" × 9"	¼–¾" × 10"	½–1" length	9" × 1" Pies	Viscous liquor
Feed Form	Ground	Ground	Pelletized, then ground	Ground	1 Raw 2 Dried 3 Extracted
Feed Size	–20 mesh	–20 mesh	–⅛ inch	–⅛ inch	–

#### *Alfalfa*

The alfalfa was delivered in pellet form and appeared to consist primarily of leaves and small stems. The primary stalks were not prominent in the pellets.

#### *Willow (Salix)*

Two separate shipments of willow were received. One shipment was from Wisconsin and a second from the State University of New York at Syracuse, New York. The shipment from Wisconsin contained uniformly cut branches approximately 10 inches in length and ¼–¾ inches in diameter. The shipment from New York also contained branches of approximately 9 inches in length and ¼–1¼ inches in diameter. The branches were ground to pass 20 mesh and were pressed into 1-inch pellets for storage. Prior to the willow being fed, the pellets were broken to pass 20 mesh.

#### *Manure*

The bovine manure used in this study was collected from the prairie lands of western North Dakota. It was a composite of three samples taken from one native prairie grassland pasture which had been grazed during the summer by one herd of mixed-breed range cows. The cows were moved in early fall and the accumulated manure dried undisturbed in the sun until November, at which time it was collected. The three samples (pies) were ground, combined, and mixed thoroughly to provide the gasification test feed.

#### **Gasification – TGA**

Gasification studies were carried out using the TGA equipment described below. The sample was loaded onto the sample pan and heated to reaction temperature as rapidly as possible (100°C/min) under argon to the target temperature. Upon reaching the target temperature, steam ( $p_{\text{H}_2\text{O}} \sim 0.1$ ) was introduced by argon carrier at 160 cm<sup>3</sup>/min. Isothermal steam–carbon reactions were carried out at ambient pressure and temperatures of 700°C (1292°F), 750°C (1382°F), and 800°C (1472°F). The reaction was typically carried out until >80% of available carbon was

gasified. First-order carbon reactivities were calculated, and Arrhenius energy of activation  $E_a$  was determined for the reactivities.

Normally, the reactivities of the feedstock can be determined by on-line monitoring of  $\text{CO}_2$  by infrared (IR) absorbance, but that was not necessary since gravimetric data were available (30). However, the black liquor contained a high concentration of  $\text{CO}_3^{2-}$ , which complicated quantitative interpretation of the  $\text{CO}_2$  spectrum since  $\text{CO}_2$  from decomposition of inorganic  $\text{CO}_3^{2-}$  contributed greatly to the total  $\text{CO}_2$ . The expected inorganic  $\text{CO}_2$  production was approximated by calculation from black liquor fed.

The TGA used in laboratory-scale gasification testing is a DuPont Model 951 module interfaced to a DuPont 2100 thermoanalyzer and data processor. The instrument has a 100-mg capacity and a maximum heatup rate of  $100^\circ\text{C}/\text{minute}$ . The sample compartment is a quartz tube through which the argon flows from the balance housing toward the exit port. A special quartz tube is used which has a sidearm through which a 1/16-inch-OD stainless steel tube is inserted to allow steam to be introduced to the sample chamber without passing through the balance housing. Typical sample sizes range around 40 mg of as-received material. Weight, time, and temperature are computer-logged for analysis.

### **Gasification – IBG**

The IBG (integrated bench-scale gasifier) is a small batch process gasifier, with a charge capacity of up to 150 g of gasification feed depending on feed density. It can be operated in the semicontinuous mode by feeding batches of material periodically during a test. This unit can provide data on the effects of bed fluidization; conversion of feedstock; reaction rate response to temperature, pressure, catalyst, and feed gas composition and flow rate; and gaseous products, while providing sufficient quantities of conversion products for subsequent analysis. The hot exhaust gas passes through the series of two condensers. Gas exiting the second condenser is collected in gas bags at 12-minute intervals to be analyzed by a refinery gas analyzer. Normally, the reactivities of feedstock can be determined by on-line monitoring of  $\text{CO}_2$  by IR absorbance. However, the black liquor contained a high concentration of  $\text{CO}_3^{2-}$ , which complicated quantitative interpretation of the  $\text{CO}_2$  spectrum since  $\text{CO}_2$  from decomposition of inorganic  $\text{CO}_3^{2-}$  contributed greatly to the total  $\text{CO}_2$ . The expected inorganic  $\text{CO}_2$  production can be approximated by calculation from black liquor fed. The black liquor contains substantial sodium, which, if it could be collected, could be reused in the pulping industry, thus greatly improving the economics of the pulping industry. Initial IBG tests were carried out at  $850^\circ\text{C}$  (1123 K) to reduce the sodium, vaporize it, and collect it downstream for possible reuse in the pulping process.

### **Product Analysis**

Product from tests was solid (ash), liquid (tar), and gas. The solid was not analyzed. Tar was separated on an open chromatographic column to determine light aliphatics, heavy aliphatics, aromatics, and polar organic compounds. Analysis of the gas product was carried out using on-line Fourier transform infrared spectroscopy (FT-IR). For selected tests, gas was collected periodically and analyzed using a refinery gas analyzer GC (gas chromatograph).

## RESULTS AND DISCUSSION

The proximate/ultimate analysis results obtained with the respective feeds are given in Table 3. Prior to reactivity studies, the black liquor was devolatilized to remove excess water and water of crystallization.

Reactivities obtained at the specified temperatures and the energies of activation for the substrates under uncatalyzed conditions are shown in Table 4. The preexponential (frequency) factors over this range of temperatures for alfalfa, black liquor, manure, and willow were  $1.6 \times 10^{12}$ ,  $6.3 \times 10^{13}$ ,  $4.2 \times 10^{18}$ , and  $3.7 \times 10^{20}$ , respectively. This factor is the y intercept of the Arrhenius plot and approximates collision frequency. Lower frequency factors relate higher ratio of effective collisions to total collisions in achieving molecular transitions.

TABLE 3

	Proximate/Ultime Analysis Results							
	Hardwood Black Liquor		Cow Manure		Willow		Alfalfa	
	As-Received		Dried-110°C/1hr		As-Received		As-Received	
	AR	MF	AR	MF	AR	MF	AR	MF
Moisture	32.39	–	2.72	–	3.23	–	9.48	–
Volatile Matter	48.00	71.00	46.77	48.08	78.56	81.18	67.40	74.45
Combust. Ash	2.65	3.92	9.55	9.82	16.12	16.66	16.23	17.93
	16.97	25.10	40.96	42.11	2.09	2.16	6.89	7.61
	<b>Dried</b>	<b>MAF</b>	<b>Dried</b>	<b>MAF</b>	<b>Dried</b>	<b>MAF</b>	<b>Dried</b>	<b>MAF</b>
Carbon	22.47	44.37	31.24	55.47	48.09	50.79	43.66	52.20
Hydrogen	5.82	11.49	3.82	6.78	5.85	6.17	5.61	6.71
Nitrogen	0.30	0.59	1.93	3.43	1.35	1.43	3.25	3.89
Oxygen (diff.)	17.91	35.37	19.04	33.81	39.40	41.61	31.11	37.20
Sulfur	4.14	8.18	0.29	0.51	0.00	0.00	0.01	0.01
Moisture (Karl Fischer)	32.39	–	2.72	–	3.23	–	9.48	–
Inorganics	16.97	–	40.96	–	2.09	–	6.89	–

Three feedstocks, black liquor, alfalfa, and willow, were gasified in the IBG. Gasification products from three biomass feeds were partitioned into three phases: solid residue, most of which was found in the reactor as ash but a small amount was deposited in the piping leading to the condensers; liquid, of which only the organic portion (tar) is reported here; and moisture-free gas, which was determined by difference. Initial tests were performed without tar cracking to determine quantities of each phase produced during the gasification reaction. Additional experiments are needed to determine the efficiency of tar-cracking catalysts in converting the tar (liquid) phase to the gaseous phase (2). Organic matter was removed from condensate by

TABLE 4

Reactivities and Arrhenius Energy of Activation ( $E_a$ ) for Steam-Gasified Biomass							
Temp., K:	973	1023	1073	1123	1173	A	$E_a$
Feed	Reactivity, /hr					Frequency Factor, $\text{sec}^{-1}$	kcal/mol
Devol. BL	2.15	5.16	12.67	–	–	$6.3 \times 10^{13}$	36.7
Devd., Ext. BL	1.61	2.72	4.84	–	–	$1.4 \times 10^8$	22.8
Alfalfa	6.58	7.07	24.8	–	42.1	$1.6 \times 10^{12}$	20.1
Willow	0.33	0.75	2.3	10.0	–	$3.7 \times 10^{20}$	48.9
Cow Manure	1.28	2.99	10.64	–	–	$4.2 \times 10^{18}$	43.6

methylene chloride extraction of acid, base, and neutral fractions and added to the tar collected from the reactor system. These products are reported in Table 5. Less than 0.5 g of char was recovered from the reactor. Most of the remainder was found in the feeder system and valves close to the reactor where it did not experience the gasification reaction. No deposits of sodium metal or salts were found in the reactor or the downstream piping. It was assumed that the sodium dissolved in the condensate and, therefore, was not economically recoverable.

TABLE 5

Gasification Products by Phase (MF)			
	Alfalfa, wt%	Willow, wt%	Black Liquor, wt%
Char	7.73	3.00	14.34
Tar	10.83	10.54	5.16
Gas (difference)	81.44	86.46	80.50

The tar was partially characterized by separating it into alkane, waxes, aromatics, and polar fractions using a specially developed technique referred to locally as "short column chromatography," which is an application of activated silica gel open column chromatography. The results of this analysis are shown in Table 6. The black liquor produced only approximately one-half the tar of the other two feeds, probably due to the tar-cracking properties of the alkali metal (sodium), but nearly 3 times as much aromatic material per gram of tar.

TABLE 6

Column Chromatographic Separation of Tars			
	Willow	Alfalfa	Black Liquor
Compound Class	wt%	wt%	wt%
Aliphatics			
Alkanes	5.9	0.8	3.9
Waxes	4.5	2.0	9.1
Aromatics	20.9	18.3	53.7
Polars	68.8	78.9	33.4

Although there was reason to believe that elemental sodium would be produced in the highly reducing atmosphere of the black liquor gasification reaction, evidence of the highly reactive metal was not found. Since the IBG tests were conducted at temperatures near the boiling point of sodium, the ion may have been reduced to the elemental form and then boiled off to be deposited downstream. Again, no evidence of elemental sodium was found, leading to the conclusion that it was deposited with the condensate in the condensers downstream of the reactor. No sodium analysis was performed on the condensate in this test. However, since recovery of sodium is of interest in the commercial world, the next test must include location and quantitation of the sodium.

The raw biomass, i.e., the biomass that had not undergone previous processing, produced less waxes and significantly more polar material than the black liquor which resulted from processing Aspen trees in the wood-pulping process. The tar produced when the black liquor was gasified produced nearly three times the aromatic material than did the other gasified biomass. The pulping process involves both heat and chemical treatment of debarked trees, resulting in removal of lignin, most of which is found in the black liquor and serves as the carbonaceous material involved in gasification. The sodium from the chemicals used in the pulping process is also found in the black liquor and serves as a gasification catalyst, thus explaining the higher reactivity shown in Table 4. None of the other biomass gasification tests involved added mineral catalysis. The reactivity of the alfalfa, a legume which is rich in nitrogen, was much greater than that of manure or willow, probably due to its thin, leafy nature, decreasing diffusion control of the reaction, and the relatively high nitrogen content, which serves as an inherent catalyst.

The product gas produced during the reactions was rich in hydrogen as shown in Figure 1. In accordance with classical kinetics, as the temperature of the reaction increased, so did the reaction rate as indicated by the reactivities shown in Table 4. H<sub>2</sub> production increased as temperature increased, as did CO<sub>2</sub> except at the highest temperature shown in Table 6 for the black liquor and willow gasification. Again, as predicted by theory and shown by Figures 2 and 3, the shift in equilibrium of the exothermic water–gas shift reaction decreased CO consumption at the higher temperatures, producing less CO<sub>2</sub> in the reactor. As the gas moves downstream and cools, however, the water–gas shift reaction shifts away from the CO, resulting in additional H<sub>2</sub> production.

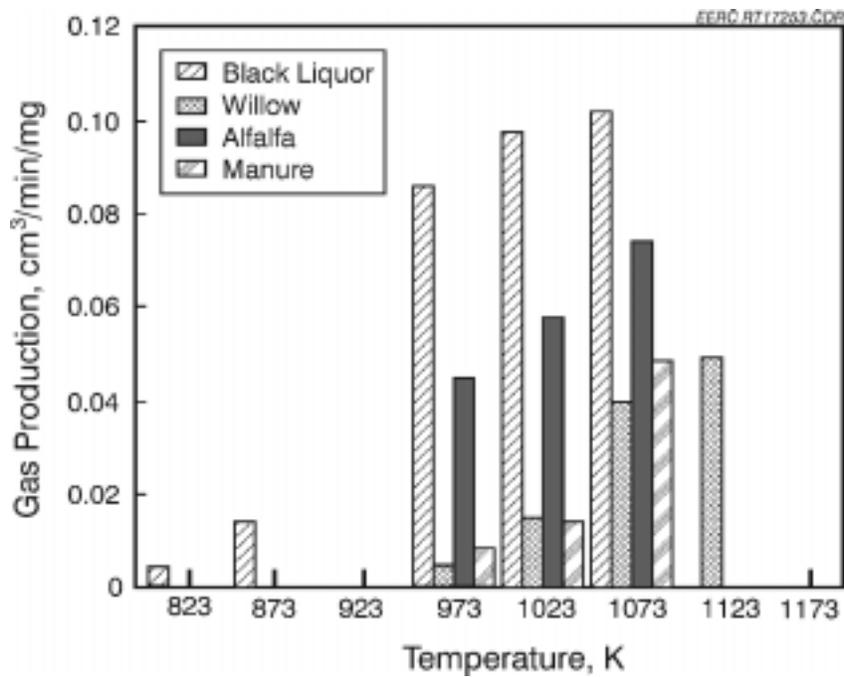


Figure 1. Hydrogen production from biomass at several temperatures.

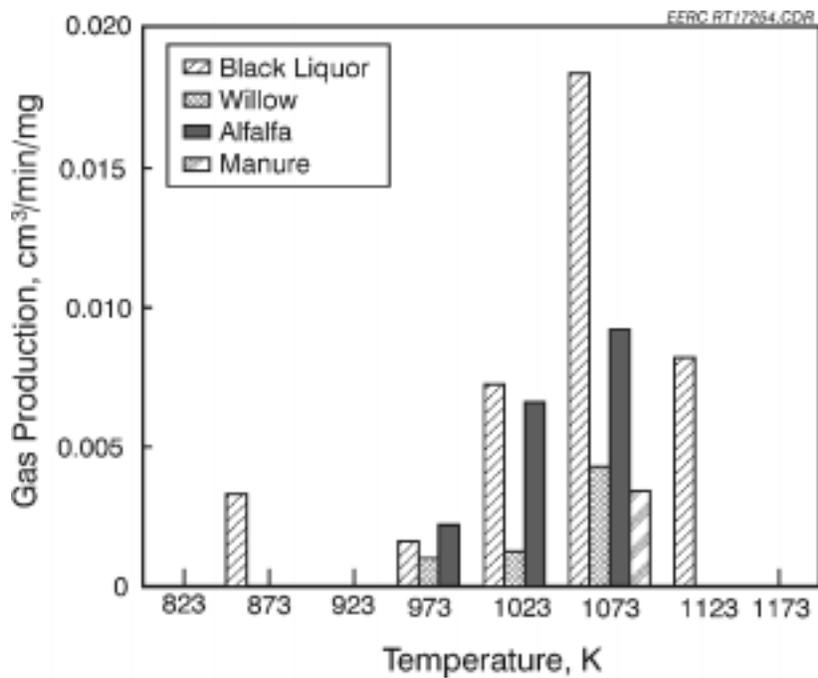


Figure 2. Carbon dioxide production from biomass at several temperatures.

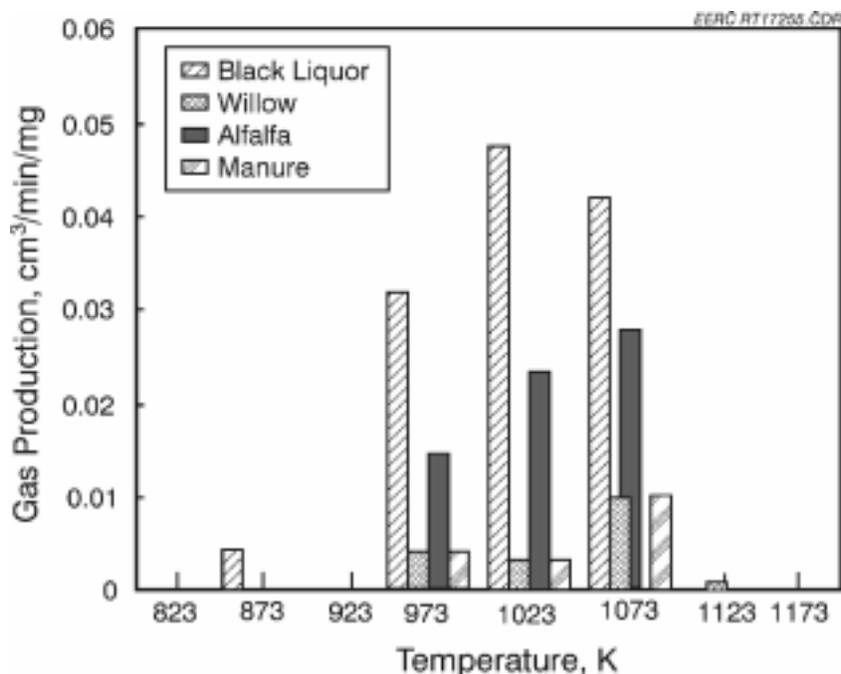


Figure 3. Carbon monoxide production from biomass at several temperatures.

Real-time analysis of the product gas from gasification tests carried out on the IBG was obtained with FT-IR spectroscopy. Hydrogen, oxygen, and nitrogen gases are transparent to FT-IR and are not detected by this technique. However, hydrocarbons, sulfur gases, carbon oxides, and nitrogen oxides have unique signals and can be detected and plotted versus time to track the progress of the reaction.

Figures 4–8 show the production of five of these gases against reaction time. Figure 4 shows that most of the methane is produced early in the reaction and is probably the result of cracking rather than reaction of synthesis gas. As reaction continues, some methane continues to be produced because of the synthesis gas reaction. Figure 5 shows that carbon dioxide is produced in huge quantities from the alfalfa as gasification proceeds. Lesser amounts of  $\text{CO}_2$  are produced by willow and black liquor. The larger amount of CO produced from gasification of black liquor and shown in Figure 6 is due to a larger quantity by weight of feed than with alfalfa and willow. Black liquor contain much more sulfur than the other feeds, as shown in Table 3, resulting in more  $\text{SO}_2$  than produced by the others. The profiles of  $\text{SO}_2$  and  $\text{CH}_4$  production in Tables 7 and 4, respectively, indicated that the sulfur was probably released from carbon as cracking and reduction occurred. (Note that absorbance of both are nearly the same. However, because of differences in molar absorptivity of the two species, it cannot be assumed that they were formed in equal concentrations.) The production of  $\text{NO}_2$  was approximately the same for the three feedstock even though the black liquor contained significantly less nitrogen than the other two feedstocks, as indicated by Table 3. The production of gases indicated by these plots indicates that the reactions were essentially complete in 1 hour or less.

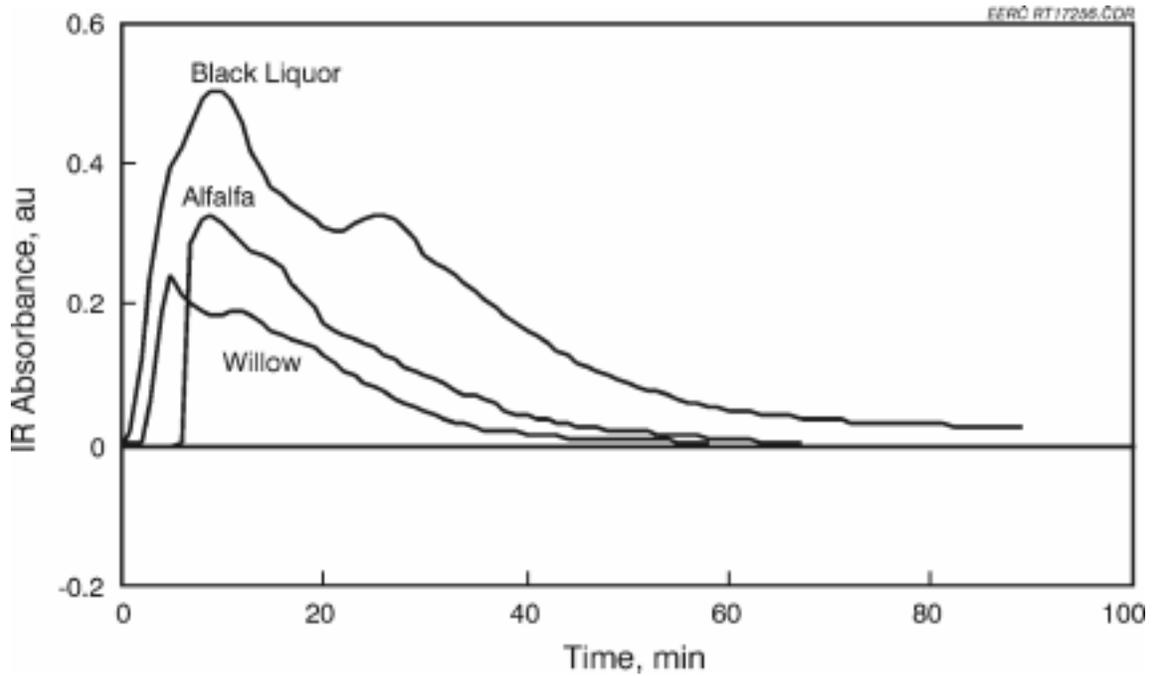


Figure 4. IR chromatogram of methane production from gasification of black liquor, alfalfa, and willow.

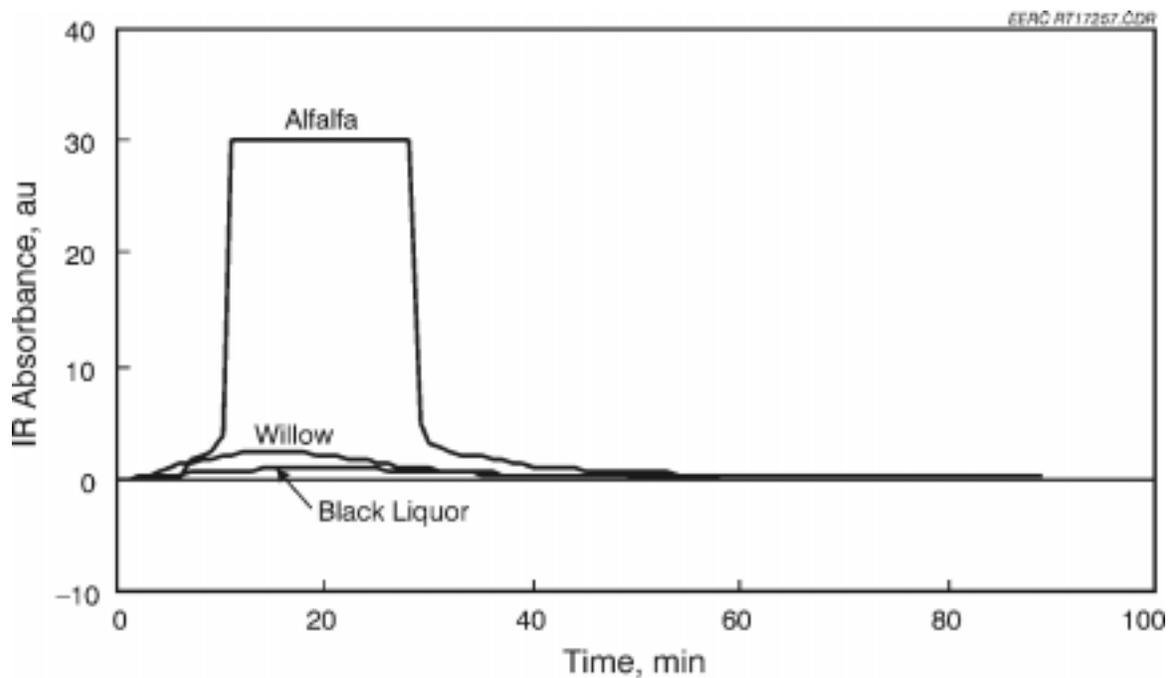


Figure 5. IR chromatogram of carbon dioxide production from gasification of black liquor, alfalfa, and willow.

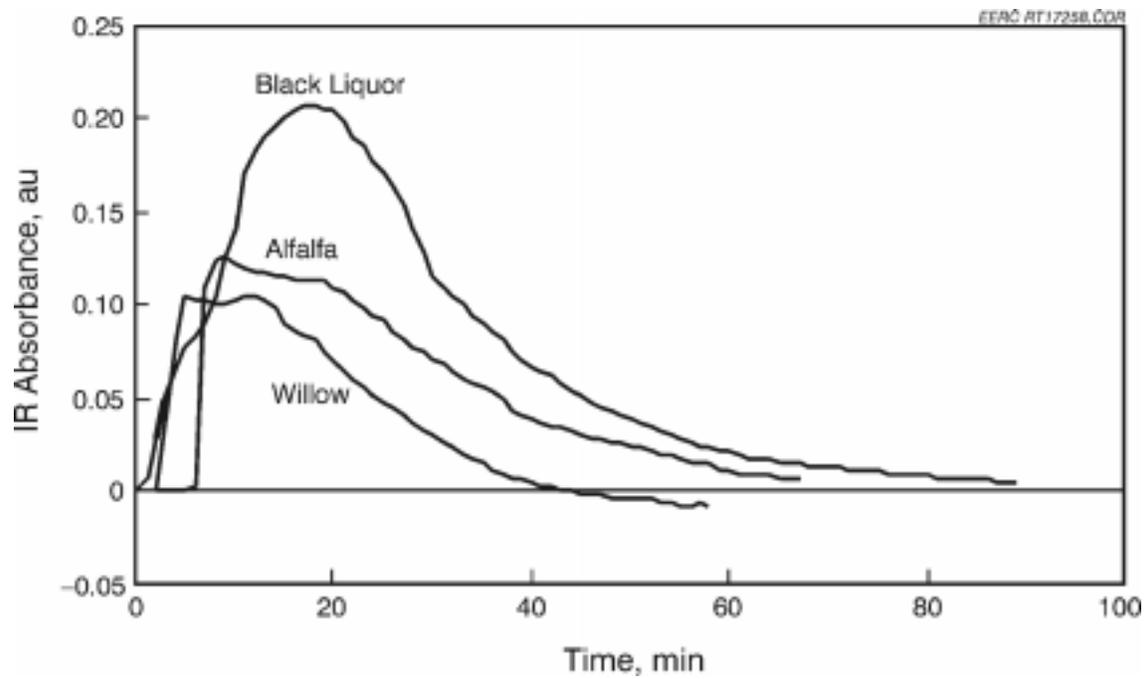


Figure 6. IR chromatogram of carbon monoxide production from gasification of black liquor, alfalfa, and willow.

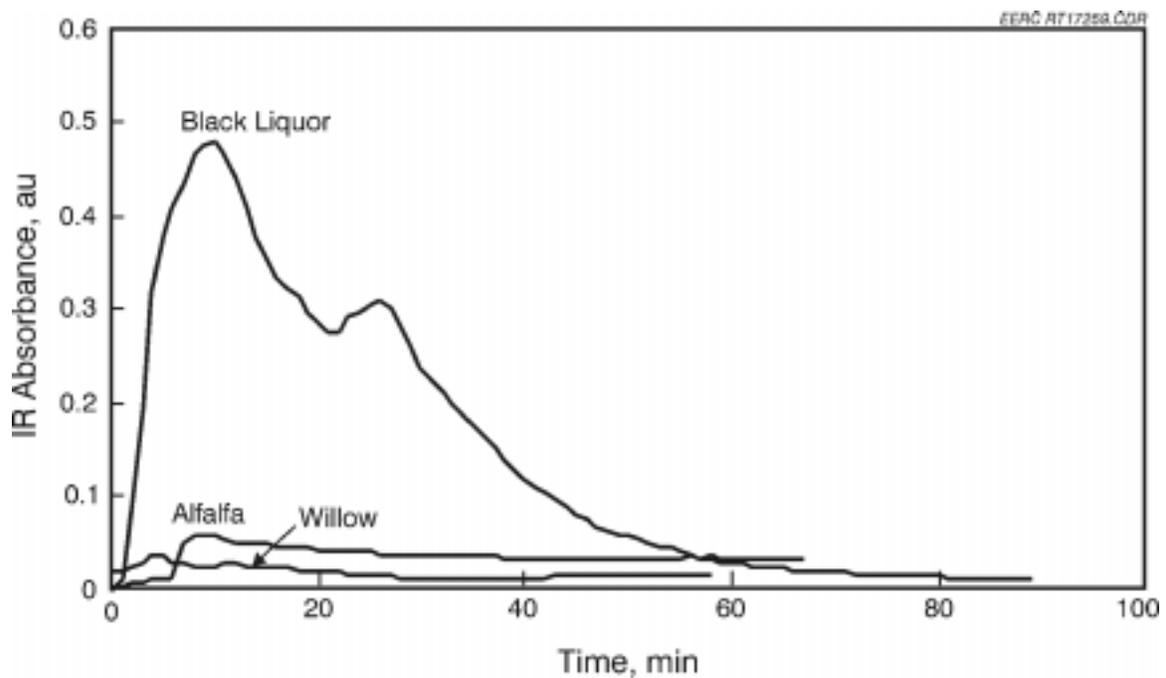


Figure 7. IR chromatogram of sulfur dioxide production from gasification of black liquor, alfalfa, and willow.

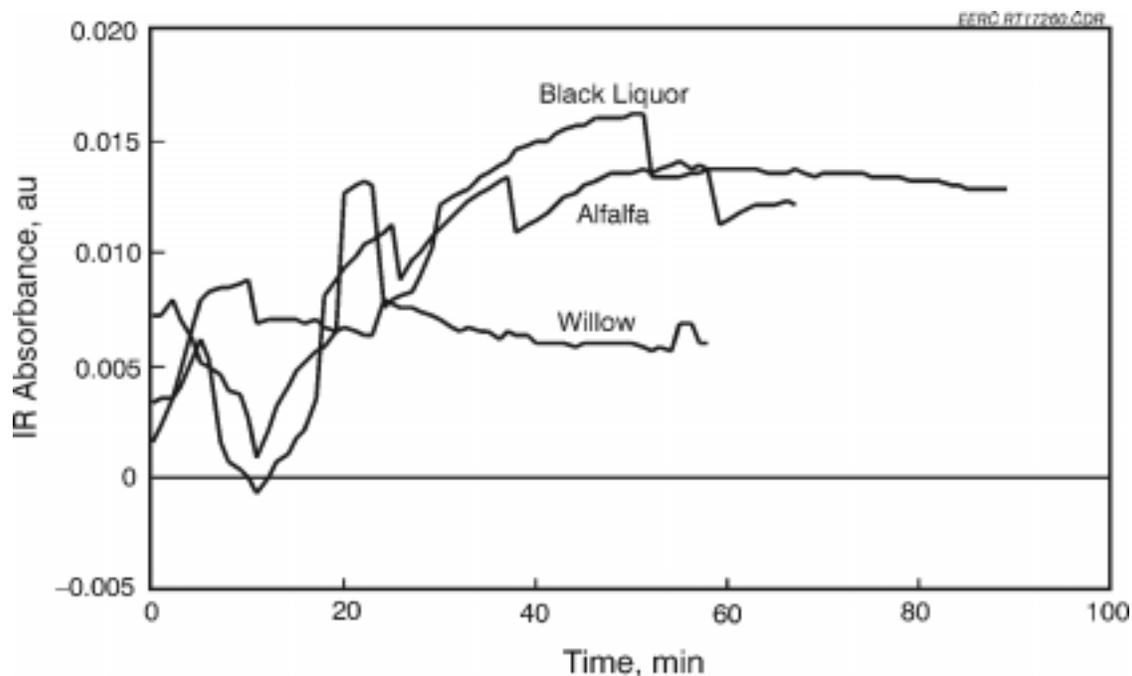


Figure 8. IR chromatogram of nitrogen dioxide production from gasification of black liquor, alfalfa, and willow.

TABLE 7

XRF Analysis of Black Liquor Ash at Two Temperatures

Element	Symbol	Ash at 600°C Concentration, wt%	Ash at 750°C Concentration, wt%
Silicon	Si	2.4	4.5
Aluminum	Al	0.9	0.8
Iron	Fe	0.1	0.1
Titanium	Ti	0.0	0.0
Phosphorus	P	0.0	0.0
Calcium	Ca	0.2	0.3
Magnesium	Mg	0.0	0.0
Sodium	Na	70.3	70.5
Potassium	K	18.6	16.7
Sulfur	S	7.4	7.0

Ash from black liquor was prepared at 600° and 750°C and then was analyzed by x-ray fluorescence (XRF) spectrometry. The results are shown in Table 7. The high levels of sodium

and potassium, both excellent gasification catalysts, account for the gasification rate and small amount of ash residue following gasification. The lack of solid residue in the gasifier after reaction suggests that when the black liquor is gasified the reducing atmosphere at nominally 850°C results in chemical reduction of catalyst followed by removal from the reactor by vaporization. Boiling points of elemental sodium and potassium are 881° and 757°C, respectively.

## CONCLUSIONS

- The values of reactivities were in the order willow<cow manure<black liquor<alfalfa at all test temperatures between 1292–1472 K. The data indicate that lowering the temperature for uncatalyzed gasification of willow and cow manure below 1292 K is not practical.
- At 1562 K, the reactivity of willow, manure, and black liquor was nearly the same, indicating success in gasifying each of the feeds tested at that temperature.
- The ash from black liquor contains approximately 70% sodium, a good gasification catalyst, thus suggesting that the gasification temperature of 1292 K could be lowered.
- Black liquor is a viscous liquid at room temperature but flows freely at elevated temperatures, making it easy to feed.
- Alfalfa had the highest reactivity of the feeds tested, but its bulk density and cost make it questionable gasification feedstock.
- No evidence of elemental sodium deposits from gasifying black liquor was found. This reduces the potential danger in handling deposits of sodium metal. Lowering the temperature of the gasification would increase potential for recovering sodium for re-use.
- Catalysis of gasification reactions by sodium introduces potential for agglomeration in the reactor. However, feeding liquid black liquor removes the need for bed material, thus reducing the potential for agglomeration.
- Insufficient ash containing inherent gasification catalyst to enhance reaction rate is found in willow or cow manure ash.
- The marketing survey showed that gasification for distributed generation is largely geared towards biomass fuels.
- The emphasis on biomass is largely due to the current political nature of environmental concerns and due to the economic benefits of using biomass residue fuels at a site where the residue is produced.
- Fossil fuels tend to be better suited for larger-scale operations outside the realm of distributed generation.

- The status of the technology shows significant commercial experience in two areas: over 5 MWe and under 1 MWe.

Conclusions drawn in Appendix A are as follows:

- Of the larger gasification technologies, Foster Wheeler, Sydkraft, and TPS Termiska Processor show the most commercial experience with multiple commercial installations.
- Of the smaller gasification companies, several companies show significant commercial experience, including Prime Energy, Ankur, System Johansson, Chiptec, Hurst Boiler, Fluidyne, and Wellman.

## RECOMMENDATIONS

- Test black liquor gasification at lower temperatures to reduce cost of the process and improve recovery of sodium and its salts while disposing of waste.
- Coprocess black liquor with other carbon sources (coal, solid waste, biomass) added to it to take additional advantage of the catalytic activity imparted by the sodium while increasing gasification fuel content.
- Test other novel fuels, e.g., turkey (poultry) litter and sewage (animal and human) sludge, as a means of producing gas for electrical generation by disposing of waste.
- Select candidate fuel based on conversion, conditions, and economics for pilot-scale testing on a continuous basis to assess the gasification process.
- Design a gasification-generation system using commercially available equipment.
- Demonstrate small-scale electrical generation using locally available feedstock.

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## **APPENDIX A**

# **GASIFICATION FOR DISTRIBUTED GENERATION: A MARKET SURVEY**

# **GASIFICATION FOR DISTRIBUTED GENERATION: A MARKET SURVEY**

## **INTRODUCTION**

Distributed generation typically applies to relatively small power generation technologies typically under 30 MWe that produce power at or near the end users. When a power plant is located close to the consumer, the technology can usually support the economics of the existing distribution grid and provide higher reliability of service and higher efficiency by utilization of waste heat.

In this report, we are looking at emerging gasification technologies that can provide power under 30 MW in a distributed generation setting. Larger-scale gasification has been used commercially for more than 50 years to produce clean synthesis gas for the refining, chemical, and power industries. Commercial-scale gasification activities are under way at 113 sites in 22 countries in North and South America, Europe, Asia, Africa, and Australia according to the Gasification Technologies Council (1).

Two major areas provide the backbone of experience in commercial gasification. This includes experience gathered from past town gas systems, when the economics favored distributed synthesis gas from coal to provide lighting and heat, and current major commercial projects supporting refining, chemical, and power industries. The majority of these commercial gasification projects are fired with coal and petroleum in which 11.1 billion standard cubic feet per day are produced, equivalent to 535,000 barrels of oil. Between 1996 and 1998, power production from gasification has seen a 22% increase. When the overall gasification market is assessed, coal accounts for 40% of the feedstock being used, and power makes up 26% of the final product. The majority shares are petroleum at 49% and chemicals at 51%, respectively. The major players in this market include Shell, Lurgi, Prenflo, Carbona, Texaco, Destec, and KRW. Of these companies, the majority are focused on large capacity systems, which economies of scale would favor. Only a few of these companies have smaller systems available for distributed generation.

### **Market**

The market drivers for distributed generation and gasification in general include the growing distributed generation market and opportunity fuels such as biomass. What is causing the distributed generation market to grow is the increasing demand for electricity, gains in small modular power generation technologies, environmental concerns, and reliability or back up power. Gasification is likely to become a share of this market because opportunity fuels such as biomass can potentially be used in combination with I.C. (internal combustion) engines, innovative steam engines, gas turbines, microturbines, fuel cells, and Stirling engines. The domestic distributed power generation market over the next decade is expected to be 5–6 gigawatts per year (2). The global increase is expected at 20 gigawatts over the next decade.

## **Status of Technology**

The following is a list of currently available gasification technologies that could be or are being commercially applied for distributed generation. This list was gathered from sources (3–5) and provides information about the supplier, the relative size range, and the status of the technology.

### ***Battelle Columbus Laboratories, Columbus, Ohio / Burlington Electric, Burlington, Vermont / FERCO, Atlanta, Georgia***

Mark Paisley and Herman Feldmann at Battelle (Columbus) developed this technology. The reactor consists of two fluidized beds in which one operates as a gasifier and the other as a combustor. The gas from each reactor passes through separate cyclones, which cycle sand and char back to the bottom of the opposing reactor. The flue gas from the combustor is used for waste heat recovery, and the gas from the gasifier is used to raise steam for gasification then cooled, scrubbed, and sent to a power plant combustion boiler. The advantage is that the process is capable of producing a high-energy gas (500 Btu/scf) at atmospheric conditions using air and not pure oxygen. The process has been licensed to Future Energy Resources Corporation (FERCO). Construction of a 10-inch-diameter reactor was completed at Battelle in 1980 under sponsorship from the U.S. Department of Energy (DOE). The plant was operated until 1986. Approximately 8000 hours of operating experience using RDF (refuse-derived fuel) was gained during 1988, and new tests have been carried out during the 1990s on a proprietary catalyst system. Currently, this test reactor is available and is being used relative to a 15-MWe scaled-up version at the McNeil Power Plant in Burlington, Vermont.

In 1984, Burlington Electric commissioned the world's largest wood power plant, using 85 tons/hr to generate 50 MWe. The McNeil plant relies on wood supplies from Vermont's forests. The power plant is capable of burning gas, oil, or wood and does so depending on fuel prices. It currently burns wood most of the time.

In 1998, a 15-MWe Battelle gasifier was constructed at the McNeil power plant site. Start-up continued through 1999, and in late August 1999, the gasification system achieved full steam gasification, energy transfer with hot sand, and self-sustaining process operation and supplied 80 M Btu to the McNeil Power plant.

### ***Carbona Inc. Tampere, Finland; subsidiary located in Atlanta, Georgia***

In 1996, Carbona Inc. was formed from a management buyout to the rights of Enviropower's fluidized-bed gasification technology. Tampella Power and Vattenfall formerly owned Enviropower. The technology is capable of gasifying biomass or coal and continues activities in three locations; Tampere and Helsinki, Finland, and Atlanta, Georgia, USA. Carbona's technology is basically an integrated gasification combined cycle (IGCC) technology. The gasifier is a pressurized fluidized bed using dolomite or sand as bed material and operates at about 1800°F. The hot-gas cleanup consists of a cyclone, gas cooler, and ceramic filter operating at about 1200°F. The product gas is used to fuel a combined-cycle gas turbine.

Carbona has a 2-ft-diameter  $\times$  65-ft-tall reactor in Tampere, Finland. It consumes 8000 lb/hr of fuel and produces 15 to 20 MW<sub>th</sub> of energy, which is currently used for district heating. As of 1996, the reactor completed 24 test runs using biomass, coal, lignite, straw, papermill residues, and willow. A total of 1600 hours have been logged burning 5100 tons of material.

Carbona also works on other gasifier types including downdraft fixed bed in the 0.1–0.5 MWe range and small fluidized beds in the 0.5- to 5-MWe range. These gasifiers are intended for reciprocating engine operation. Carbona was involved with a 75-MWe power plant that was to be built in Minnesota using alfalfa as an energy crop. When DOE pulled its interest from the project, other interests folded as well.

### ***Elsam/Elkraft Ballerup, Denmark***

Elsam and Elkraft are two utility groups in Denmark who launched a large R&D program geared toward implementation of biomass power. The project was initiated in 1992 and completed in June 1995 with financial support from the European Commission under the APAS clean coal technology program. Results regarding gasification included characterization of co-gasifying straw and coal, analysis of the feed, effects of various mix ratios, physical handling, and modeling of IGCC plants. Reactors that were used during the testing included a laboratory reactor in Riso, Denmark, a 3 MW pressurized entrained flow gasifier (NOELL, Germany), and a 0.3 MW and 15 MW fluidized bed gasifiers at (VTT, Finland).

### ***Foster Wheeler – Karhula, Finland, Research Facility***

Foster Wheeler is a commercial company manufacturing boiler and gasifiers with approximately 12 years experience in gasification technology. Foster Wheeler employs 12,000 people and has net sales in the range of US\$2.3 billion. Foster Wheeler has purchased the former Ahlstrom Corporation, which manufactures Pyroflow – atmospheric fluidized-bed gasifiers. A pilot-scale reactor exists at the Finland location, but is currently not in use. It has been used to test wood, bark, peat, lignite, and coal. Construction of an IGCC demonstration commenced September 1991 at Varnamo. The objectives are to establish the operating costs of such a system. Six gasifiers, 3–35 MW<sub>th</sub>, have been installed between 1982 and 1986 in Finland, Sweden, and Portugal. Four of these gasifiers are known to be operational as of June 1992. The Pyroflow system was originally designed to supply gas for lime kiln operation, although power production using a diesel engine was investigated at one time. Tar removal by venturi scrubbing achieved a 98.6% efficiency; however, Foster Wheeler suggests that power production should be limited to pressurized IGCC operations.

### ***Institute of Gas Technology – Chicago, Illinois, Not-For-Profit Research Facility***

Institute of Gas Technology is home to the Renugas process, which 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 to Tampella and was part of a Hawaiian biomass project under the direction of Westinghouse that was currently abandoned (1999). The intent of the project was to gasify sugarcane bagasse for electrical power.

A pilot-scale 11-ton/day pressurized single-stage oxygen-flown fluidized-bed gasifier exists at the Chicago facility. The reactor is 6 feet in diameter and has a height of 22 feet. The bed consists of aluminum oxide beads. Air, oxygen, and steam can all be injected into the reactor, which is capable of pressurizing at 400 psig.

***EPI – Energy Products of Idaho, Coeur d’Alene, Idaho***

EPI manufactures fluidized-bed combustion and gasification systems. Updraft units previously produced have been halted because of operational difficulties. EPI previously had a 1.3-MWth gasifier on site, but currently does not have any pilot units. During the 1980s, EPI installed three gasifiers that eventually failed because of economic constraints. In 1981, a 14.2-MWth fluidized-bed gasifier was designed to provide gas to a central heating boiler using California city cleanup residue as fuel. The cleanup residue did not produce sufficient gas, and clean wood chips came in at too high of a cost to sustain operation. The second, at Alternate Gas Inc. in Bloomfield, Missouri, in 1985, was used to produce gas to fire an existing rotary kiln and fuel dryer. This plant closed because of a reduction in fossil fuel prices. The third, in 1985, was a 26.3-MWth plant for producing gas for a rankine power cycle. It was installed at Catalyst Energy/Idaho Timber Corporation’s Crisstad Power Plant in North Powder, Oregon. The plant was closed because of low availability.

***Lurgi Energie – Frankfurt, Germany***

Lurgi has a 1.7–3-MWth gasification pilot plant at its R&D (research and development) center. The unit is capable of being air- or oxygen-blown. A commercial system was installed at Zellstoffwerke Pöls AG, which is an Austrian pulp producer. The system is currently operational and runs at atmospheric conditions producing a gas from bark to fuel a lime kiln. Lurgi is investigating gasification at elevated pressures using a high-temperature Winkler process and is also investigating hydrogen production and power production using I.C. engines and gas turbines. A recent news release stated that Lurgi is to supply two biomass power plants generating from olive pulp in Spain, which will be the largest power plants in Europe exclusively fired with biomass.

***Producer Rice Mill Energy Systems (PRMES) or Prime Energy – Hot Springs, Arkansas***

Prime Energy is a commercial company that may have gasified more biomass than any system since World War II. Prime Energy has over 20 installations with 8 more planned. Generally, the company is in the business of providing systems to supply gas from biomass. The PRMES gasifier is an updraft unit originally designed to gasify rice hulls. Most of the installed systems are relatively simple with no gas cleanup prior to combustion of the gas for heat applications. One particular Prime Energy installation consists of a 7.5-MWe steam power plant at Cargill Company’s Greenville, Michigan, location.

***Sur-lite – Sante Fe Springs, California***

Sur-lite Corporation manufactures 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. It has constructed a 1.5-M Btu/hr pilot gasifier available for testing. Sur-lite has successfully gasified rice hulls, shredded tires, dried dairy manure, dried sewage sludge, and RDF. It has built a special fluid-bed gasifier for cotton gins and lime kilns available in sizes from 10 to 80 M Btu/hr (0.6 to 5 tons/hr).

***Thermochem, Inc.***

Thermochem through funding from EPA, DOE, and the California Energy Commission has developed a steam reforming gasification process for handling most waste materials to produce a hydrogen-rich medium-Btu gas. The company has three pilot plant units for testing a variety of fuels. Pilot and prototype activities are planned for 2000 and 2001.

***TPS Termiska Processer AB – Nyköping, Sweden***

TPS Termiska Processer AB is a privately owned R&D company. It employs 45 people and operates on an approximate budget of \$7M per year. TPS has developed several atmospheric circulating fluidized-bed gasifiers for various commercial clients. The gasifiers typically range in size under 15 MWe.

***Volund R&D Centre – Kolding, Denmark***

Volund Energy Systems constructed a gasifier in 1989 at a power station in Kyngby, Denmark. Elkraft owns the gasifier. Approximately 1200 hours of operating experience has been gained firing 100 tons of straw and 40 tons of wood chips. The gasifier is an updraft fixed-bed system, and the gas is provided for heat. There are plans to install a dual-fuel diesel engine at the site.

***Wellman Process Engineering, LTD – West Midland, England***

Along with the manufacture of boilers and other industrial thermal equipment, the Wellman Company has been making gasifiers for coal and wood for 75 years. Between 1923 and 1950, it produced hundreds of coal gasifiers for town gas. Wellman is currently pursuing the market for electrical power generation from wood in the 2.5- to 10-MWe range. Wellman has indicated that it has operated its updraft gasification system with a catalytic tar cracker running a Caterpillar G3406 engine for 1200 hours.

***AEW, Associated Engineering Works – Tanuku, A.P., India***

AEW builds gasifiers in the 20- to 100-kW range, which are downdraft units designed to gasify wood chips and rice hulls. They are widely used for cooking, and the company has been in business since 1986.

***Ankur Scientific Energy Technologies – Baroda, India***  
***B.G. Technologies – Washington, DC***  
***Reflective Energies – Mission Viejo, California***

Ankur Scientific has been in business since the 1980s and demonstrates the most experience in the gasification market to date with small downdraft gasifier diesel engine power systems. Ankur produces and sells units in the 10–400-kW range. Gasifiers are provided for operation using wood, coconut shells, maize cobs, cotton gin trash, etc. Ankur currently has over 80 systems in operation, mostly in India. B.G. Technologies has licensed to market the Ankur Technology globally outside of India. Reflective Energies is marketing a trailer-mounted gasification microturbine system using the Ankur technology. Plans are for development through DOE's small modular biopower program.

***Camp Lejeune Energy from Wood (CLEW) – Camp Lejeune, North Carolina***  
***Research Triangle Institute – Research Triangle Park, North Carolina***  
***Environmental Protection Agency – Research Triangle Park, North Carolina***

This project is an EPA effort to demonstrate energy conversion from biomass. It consists of a downdraft gasifier coupled to a 1-MWe natural gas spark ignition engine being used to produce electricity from wood residues produced at a military landfill. The project has completed 360 hours of run time with 115 of the hours producing electricity to the grid and represents the longest sustained operation in the United States at this size range for this technology. RTI currently holds a cooperative agreement with EPA to demonstrate the technology and is seeking further funding for operation. The technology made its first commercial appearance at a furniture manufacturer in Asheboro, North Carolina, then at a lumber operation in Ellicottville, North York, and again at Richland, Washington. The units in North Carolina and New York produced electricity for short periods, and the unit in Washington was used for waste minimization, flaring the gas. These installations were provided by Mech-Chem Associates and are no longer in operation. During the Camp Lejeune project, Thermal Technologies Incorporated of Omaha, Nebraska, bought the process patents with the intention of commercialization.

***Chiptec Wood Energy Systems – Burlington, Vermont***

Chiptec manufactures close-coupled gasifiers for existing boilers. The company was founded in 1986. Chiptec has installed over 100 units for schools, hospitals, and manufacturing plants. The Chiptec gasifier is essentially a sloping grate unit, and its heating systems are fully automated.

***Community Power Corporation – Aurora, Colorado***

Community Power Corporation is a small company working towards development of a small gasifier utility under an NREL (National Renewable Energy Laboratory) small modular biopower contract. It is currently developing a 150-kW gasifier engine system.

### ***Cratech – Tahoka, Texas***

Cratech is a privately owned company working to develop a pressurized gasification gas turbine system. The company plans to market systems in the 1- to 20-MWe range. Cratech has done very little marketing at this stage and has operated on funds from EPA, the state of Texas, and the Western Regional Biomass Energy Program. Cratech has a well-developed pressurized gasification and feed system that has been tested on wood chips, cotton gin trash, and bagasse. Currently, Cratech is are working on coupling a turbine to its process. The gasifier is a modified fluid bed.

### ***Fluidyne – Auckland, New Zealand***

Fluidyne has been working on gasification power systems since 1977. Fourteen of its 35-kWe units have been installed around the world. Fluidyne manufactures a bolt-on dual-fuel gas conversion kit designed for diesel engines that has been installed on Lister, Caterpillar, and Isuzi engines. Currently, there has not been much business for Fluidyne, but it does represent some competence in reciprocating engine operation from small gasifiers.

### ***HTV Energy – Gunzgen, Switzerland***

HTV has an operating gasifier engine system in the 750-kW size range. As of 1996, the gasifier was operated for 3500 hours and the engine 250 hours producing electricity.

### ***Hurst Boiler & Welding, Inc.***

Similar to Chiptec, this company offers close-coupled gasification boiler systems. It has installed over 400 systems. Hurst Boiler & Welding employs approximately 200 people.

### ***Shawton Engineering – England***

Shawton is developing a downdraft gasifier engine system in the 250-kW range. A system has been built and tested at 150 kW, and there are future plans for demonstration work.

### ***System Johansson Gas Producers – Midrand, South Africa***

System Johansson has at least nine gasifier installations ranging from 50 to 200 kW. Most of these gasifiers have been installed in the 1990s, and two of the installations were performed in 1983. System Johansson has experience operating reciprocating engines, but the author is unaware as to what capacity.

### ***Thermogenics – Albuquerque, New Mexico***

Thermogenics markets a unique coflow gasifier and mechanical gas cleanup system for operating a reciprocating engine. It has a prototype unit that has been extensively tested; however, Thermogenics does not have any commercial installations. Its gasifiers are offered in the 300-kW to 2-MW range.

## *Sydkraft AB – Malmö, Sweden*

Sydkraft AB has claimed to have built the world's first complete IGCC power plant in Varnamo, Sweden. The plant provides 6 MWe to the grid using wood waste as a fuel. A demonstration program is currently under way, commencing in 1996. 8500 hours of gasification runs and 3500 hours of overall plant operation have been completed. The process uses a Foster Wheeler pressurized fluidized-bed gasifier.

### **SUMMARY**

Gasification for distributed generation is largely geared towards biomass fuels. This is partly due to the current political nature of environmental concerns and due to the economic benefits of using biomass residue fuels at a site where the residue is produced. Fossil fuels tend to be better suited for larger-scale operations outside the realm of distributed generation.

The status of the technology shows significant commercial experience in two areas: over 5 MWe and under 1 MWe. Of the larger technologies, Foster Wheeler, Sydskraft, and TPS Termiska Processor show the most commercial experience with multiple commercial installations. Of the smaller gasification companies, several companies show significant commercial experience, including Prime Energy, Ankur, System Johansson, Chiptec, Hurst Boiler, Fluidyne, and Wellman. Not all of these gasifier companies have significant commercial experience generating electricity, but do demonstrate successful commercial gasifiers. Lurgi is quite successful at much larger scales and was not mentioned; however, it is expected that Lurgi could quite easily compete in the distributed generation market for gasification.

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