Biomass Thermochemical Conversion Program 1984 Annual Report

January 1985

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Biomass Program Office

Pacific Northwest Laboratory

**Operated for the U.S. Department of Energy
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BIOMASS THERMOCHEMICAL
CONVERSION PROGRAM
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Richland, Washington 99352

EXECUTIVE SUMMARY

Biomass represents an important but underutilized energy resource in the United States. The Congressional Office of Technology Assessment has estimated that, with proper resource management and the development of efficient conversion processes, the potential contribution of biomass to U.S. energy demand could range as high as 17 quadrillion Btu per year--almost 20% of current U.S. energy consumption. Similarly, the Energy Research Advisory Board (ERAB) has estimated a potential of approximately 10 quadrillion Btu per year.

Wood and crop residues constitute a vast majority of the biomass feedstocks available for conversion, and thermochemical processes are well suited for conversion of these materials. The U.S. Department of Energy (DOE) is sponsoring research on this conversion technology for renewable energy through its Biomass Thermochemical Conversion Program.

The Program is part of DOE's Biomass Energy Technology Division, Office of Renewable Energy. Pacific Northwest Laboratory has been designated the Field Management Office for the Biomass Thermochemical Conversion Program with overall responsibility for the Program. This report briefly describes the Thermochemical Conversion Program structure and summarizes the activities and major accomplishments during fiscal year 1984.

PROGRAM OBJECTIVE, GOAL, AND STRATEGY

The objective of the Biomass Thermochemical Conversion Program is to generate scientific data and conversion process information that will lead to establishment of cost-effective processes for converting biomass resources into clean fuels. The goal of the program is to develop the data base for biomass thermal conversion by investigating the fundamental aspects of conversion technologies and by exploring those parameters that are critical to the conversion processes.

PROGRAM RESEARCH AREAS

The research activities sponsored by the Thermochemical Conversion Program can be divided into four areas:

1. Gasification Technology
2. Liquid Fuels Technology
3. Direct Combustion Technology
4. Program Support Activities.

These activities are described in detail in this report. Major accomplishments in each of these areas for fiscal year 1984 are described below.

MAJOR ACCOMPLISHMENTS IN 1984

The Biomass Thermochemical Conversion Program made major progress in 1984 toward verifying the technical feasibility of several advanced technology concepts. These state-of-the-art research concepts offer the potential for significant advancement of biomass conversion technology. In addition, progress was made at the fundamental level in understanding the reaction behavior involved in upgrading biomass liquefaction products. Outstanding accomplishments of the Biomass Thermochemical Conversion Program during fiscal year 1984 include:

- Successful Operation of 3-MW Combustor/Gas Turbine System. Aerospace Research Corporation completed construction of a 3-MW combustor/gas turbine unit and successfully completed initial shakedown operations. The 3-MW unit was based on a design similar to a 375-kW unit which was operated successfully for extended periods in 1983. The larger unit was assembled at Roanoke, Virginia, and underwent initial testing at speeds up to about 25% of design maximum. Particulate measurements indicated that the combustion gases were within the specifications for the gas turbine. Based on the success of the shakedown operation, the unit is being moved to Red Boiling Springs, Tennessee, where it is being reassembled. The unit will undergo long term testing while generating power which will be sold to TVA. This research is the first to successfully use biomass solid fuels to directly power a gas turbine.
- Successful Extended Term Operation of an Indirectly Heated, Dual Bed Gasifier for Producing Medium-Btu Gas. Battelle Columbus Laboratory

successfully operated a dual bed, indirectly heated biomass gasifier for extended periods of up to about 72 hours. The gasifier components operated as planned, and shutdown was voluntary. The results from the extended, steady-state operation closely matched those from shorter runs, and enabled better mass and energy balances to be determined.

- Determination That Oxygen Requirements for Medium-Btu Gasification of Biomass in a Pressurized, Fluidized Bed Gasifier are Low. The Institute of Gas Technology (IGT) operated a pressurized, fluidized bed gasifier to determine the actual oxygen requirements for producing medium-Btu gas from biomass. Under typical conditions (325 psia pressure, 1500°F), the steam requirement is in the range of 0.5 to 0.8 lb/lb wood and the oxygen requirement ranged from 0.21 to 0.34 lb/lb wood. This very low oxygen requirement has favorable impact on projected process economics.
- Established Interdependence of Temperature and Residence Times on Biomass Pyrolysis Oil Yields. Georgia Tech Research Corporation performed experiments in an entrained flow pyrolysis reactor to generate low cost liquid fuels from biomass. Biomass pyrolysis oil yields up to about 55% by weight on a moisture and ash free basis were obtained. Studies show that short residence times will give higher mass yields, and reactor modifications are currently underway to accommodate these predictions.
- Determination of Preliminary Technical Feasibility of Thermally Gasifying High Moisture Biomass Feedstocks. Pacific Northwest Laboratory showed the technical feasibility of thermochemically converting high moisture biomass feedstocks into medium-Btu fuel gases. The concept uses a nickel/carbonate catalyst at moderate temperatures (approx. 450°C) and high pressures (4000 psi) to produce a methane-rich gas. High moisture feedstocks such as grasses and food processing wastes were converted to gases with about 300-400 Btu/scf. This work indicates that thermochemical conversion processes may be suitable for even very moist biomass feedstocks.

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BIOMASS THERMOCHEMICAL CONVERSION PROGRAM
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INTRODUCTION

Biomass represents an important but underutilized energy resource in the United States. Wood and forest product residues, grasses, agricultural crops and their residues, animal wastes, and other biomass resources currently supply nearly 3% of total U.S. energy consumption. As an abundant, renewable, domestic energy resource, biomass can help the United States reduce its dependence on imported oil and natural gas.

The Office of Technology Assessment has estimated that, with proper resource management and the development of efficient conversion processes, the potential contribution of biomass to the U.S. energy demand could range as high as 17 quadrillion Btu per year.^(a) This amounts to almost 20% of current U.S. energy consumption. Similarly, the Energy Research Advisory Board (ERAB) has estimated that biomass could potentially supply the nation with about 10 quadrillion Btu by the year 2000.^(b) Thermochemical conversion processes are expected to contribute significantly to this total.

The U.S. Department of Energy (DOE) is actively encouraging increased utilization of biomass resources through research projects sponsored by its Biomass Energy Technology Division, Office of Renewable Energy. Pacific Northwest Laboratory (PNL)^(c) has been designated the Field Management Office for the Biomass Thermochemical Conversion Program. As such, PNL has responsibility for overall management of the program.

This report first describes the Biomass Thermochemical Conversion Program: its organization, underlying objective, and goal, rationale, and

(a) Office of Technology Assessment. 1980. Energy from Biological Processes, Volume I - Biomass Resource Base. U.S. Government Printing Office, Washington, D.C.

(b) Solar Energy Research and Development: Federal and Private Sector Roles, Draft Report to the Solar R&D Panel of the Energy Research Advisory Board, September 2, 1982.

(c) Operated for the U.S. Department of Energy by Battelle Memorial Institute.

approach. The program subcontracted research activities during fiscal year 1984 are then documented. Program publications issued in FY84 are listed in the Appendix.

PROGRAM DESCRIPTION

The Biomass Thermochemical Conversion Program began in 1977 as one aspect of DOE's overall effort to develop renewable energy resources in the U.S. The recognized potential of biomass as a significant contributor to meet the nation's energy demand suggested the need for research into more efficient processes for converting the resource into usable energy. This section describes the Thermochemical Conversion Program's role in meeting that need.

ORGANIZATION

The relationship of the Biomass Thermochemical Conversion Program to other programs within DOE's Biomass Energy Technology Division is shown in Figure 1.

FIGURE 1. Relationship of Biomass Thermochemical Conversion Program to Biomass Energy Technology Division Organization

OBJECTIVE AND GOAL

The objective of the Biomass Thermochemical Conversion Program is to generate scientific data and biomass conversion process information that will lead to establishment of cost-effective processes for conversion of biomass resources into clean fuels. Areas of research included in the program are gasification, liquid fuels production, and combustion of biomass. The goal of

the program is to improve the data base for biomass conversion by investigating those parameters that are critical to thermal conversion processes.

RATIONALE

Thermochemical conversion processes employ elevated temperatures to convert biomass materials to more useful energy forms. Process examples include:

- combustion to produce heat, steam, electricity, direct mechanical power, and combinations of these
- gasification to produce low- or intermediate-energy fuel gas
- gasification to produce synthesis gas for the production of high-value liquid and gaseous fuels
- direct liquefaction to produce heavy oils or, with upgrading, lighter boiling liquid products
- pyrolysis to produce a mixture of pyrolysis oils, fuel gases, and char.

Wood and crop residues comprise 96% of biomass feedstocks available for conversion to liquid and gaseous fuels. Thermochemical processes are well suited for conversion of these materials. These processes can convert 85 to 95% of the organic material in such feedstocks with high efficiency and relatively little sensitivity to variations in the feed material. As illustrated in Figure 2, thermochemical conversion processes can provide a wide spectrum of versatile products congruent with U.S. energy use patterns.

FIGURE 2. Thermochemical Conversion Can Provide a Wide Spectrum of Products

Compared to other solid fuels such as coal, biomass feedstocks have unique properties that offer great potential advantages for thermochemical conversion processes. These properties include:

- high volatility - Biomass feedstocks contain a high proportion of volatile material, 70 to 90% for wood compared to 30 to 45% for typical coals. This means that a large fraction of most biomass feedstocks can be pyrolyzed (devolatilized) rapidly at relatively low temperatures. Figure 3 presents a comparison of wood and one typical coal in terms of weight loss due to devolatilization at various temperatures. Figure 3 presents a comparison of wood and one typical coal in terms of weight loss due to devolatilization at various temperatures.

SOURCE: M. J. ANTAL, BIOMASS ENERGY ENHANCEMENT-A REPORT TO THE PRESIDENT'S COUNCIL ON ENVIRONMENTAL QUALITY (PRINCETON, N.J., PRINCETON UNIVERSITY, JULY 1978).

FIGURE 3. Biomass is More Volatile Than Coal

FIGURE 4. Biomass Chars Gasify Very Rapidly

- high char reactivity - Biomass chars gasify rapidly in the presence of steam at relatively low temperatures. This property is illustrated in Figure 4, which compares the char reactivity of some biomass feedstocks with peat and coal chars at 800°C and 300 psi in the presence of steam.
- low sulfur content - Typical wood feedstocks contain less than 0.2% sulfur, which greatly reduces gas cleanup costs and allows biomass to be reacted in the presence of catalysts without sulfur poisoning problems.

- low ash content - Wood and most other biomass feedstocks contain less than 3.0% ash. Ash removal systems are simplified and ash disposal costs are reduced.

The combination of these four properties makes it possible to convert biomass feedstocks into gaseous and liquid fuels at faster rates and lower temperatures, and with fewer waste disposal problems, than most coals.

Thus, biomass feedstocks have some potential advantages when compared to fossil feedstocks. However, biomass is a widely distributed resource with a relatively high moisture content. This disadvantage limits the distance over which it can be shipped economically. Developing conversion processes that exploit the unique properties of biomass feedstocks will result in higher conversion rates and lower costs. This will allow biomass-derived gaseous and liquid fuels to be produced competitively in smaller-scale facilities.

APPROACH

To achieve its objective and goal, the Thermochemical Conversion Program sponsors research and development activities with high payoff potential. Innovative basic research concepts are initially selected on the basis of program research needs, the concepts' potential contribution to advancing the state-of-the-art of biomass conversion, and the availability of research funds.

Initial research usually consists of determining the technical feasibility of individual concepts in bench-scale experiments. Concepts passing the preliminary technical feasibility test are studied in continuous process research units. These small-scale research units permit further investigation of the concept under realistic conditions in a continuous, dynamic, interactive mode. This research stage allows the evaluation of variations in operating parameters in a continuous process environment and the determination of material and energy balances critical to determining the potential of the process. Individual concepts are then combined into an integrated process. The integrated process is evaluated to estimate process economics at commercial scale. This research approach is shown conceptually in Figure 5.

FIGURE 5. Program Approach

The interaction between the federal government and private industry in funding research on evolving technologies is shown in Figure 6. To assure the maximum opportunity for technology transfer to the private sector, industrial interest and involvement is sought at all stages of research. The government role is primarily to explore basic research concepts and establish the technical feasibility of promising technologies. These early stages of research involve risks that are too great and lead times that are too long to be supported by industry. As the data base for evolving technologies becomes better defined, cost-sharing by both the government and private industry becomes more practical.

FIGURE 6. Industry Participation in the DOE Program

PROGRAM RESEARCH AREAS

The Biomass Thermochemical Conversion Program sponsored research in four major areas during FY 1984:

1. gasification technology
2. liquid fuels technology
3. combustion technology
4. program support research.

The following subsections present descriptions of the specific projects conducted in each of these areas. Publications documenting the details of these projects are listed by research area in the Appendix.

GASIFICATION TECHNOLOGY

Gasification of biomass can be achieved by reacting biomass with steam, at moderately high temperatures, to produce a combustible gas containing large quantities of hydrogen and carbon monoxide. Heat is provided to the reactor either by combusting a portion of the biomass with air or oxygen, or by indirectly heating the reactor.

If air is used to heat the gasifier, the nitrogen in the air significantly dilutes the product gas, and a low-Btu gas is produced, as shown in Figure 7. Low-Btu gas typically has a heating value ranging from 90 to 200 Btu/scf. Today, low-Btu gasification of biomass is considered to be a commercial or near-commercial technology. Low-Btu gas can substitute for natural gas and oil to fire boilers, subject to the following limitations:

- Low-Btu gasifiers must be close-coupled to boilers to take advantage of the high temperature of the gas leaving the gasifier.
- Burning low-Btu gas in a boiler designed for oil or natural gas will frequently result in boiler derating unless expensive modifications are made to the boiler.

Low-Btu gas can also be used instead of gasoline and diesel fuel to fire internal combustion engines, provided that the gas is sufficiently cleaned and cooled. However, the efficiency of the engine will be reduced by about 20%.

Although low-Btu gasifiers are commercially available, questions about overall reliability remain.

FIGURE 7. Thermochemical Gasification of Biomass

If nitrogen is eliminated from the product gas of a biomass gasifier by heating indirectly or with oxygen, a medium-Btu gas can be produced as shown in Figure 7. Medium-Btu gas has a heating value typically ranging from 300 to 600 Btu/scf, and is much more versatile than low-Btu gas.

Because of its higher heating value, it possesses the following advantages over low-Btu gas:

- Medium-Btu gas can be substituted for natural gas or oil in most retrofit applications without significant derating problems.
- Medium-Btu gas produces a higher flame temperature than low-Btu gas, making it suitable for retrofitting processes where this is a critical factor.
- Medium-Btu gas has two to five times the energy density of low-Btu gas, allowing it to be transported moderate distances by pipeline at a reasonable cost.
- Medium-Btu gas can be used for the synthesis of high-value products such as pipeline gas or liquid transportation fuels.

Medium-Btu fuel gas can also be produced from coal. The major disadvantage of coal gasification is that coal is not very reactive. Large quantities of oxygen are required to achieve sufficiently high reactor temperatures and reasonable reaction rates. Oxygen plants, however, are very expensive to

build and operate. This dictates that medium-Btu coal gasification plants be constructed with very large capacities to take advantage of economies of scale in order to be competitive.

Because biomass is a distributed resource, transportation costs limit the amount of biomass that can be delivered to a central facility. Consequently, biomass gasifiers are limited to a maximum capacity of about 2,000 dry tons of wood per day. Therefore, it is necessary to reduce or eliminate the requirement for oxygen to achieve a cost-effective process at a smaller scale. Fortunately, biomass is much more reactive than coal and can be gasified at lower temperatures. Less heat is required for reaction due to the higher volatile content, and the remaining chars are also more reactive, as shown in Figures 3 and 4. This reduces the oxygen requirement for medium-Btu gasifiers that are directly heated with oxygen. Furthermore, the lower reactor temperatures and heating requirements make it possible to indirectly heat the biomass in the reactor without using expensive, exotic heat exchanger materials, thereby eliminating the requirement for oxygen. This approach offers the opportunity for significantly reducing gasification costs. In addition, the low sulfur content of most biomass feedstocks makes it possible to gasify biomass in the presence of catalysts without catalyst poisoning problems. As a result, smaller conversion facilities can be economically feasible if the conversion process capitalizes on the unique characteristics of the biomass feedstock. The lower sulfur content also eliminates the need for a costly gas cleanup system to remove sulfur from the product gas.

The gasification research projects sponsored by the Biomass Thermochemical Conversion Program are directed primarily toward exploiting the natural advantages of biomass to produce medium-Btu gas. The medium-Btu gas, depending on process concept, can be utilized either as a fuel gas or as a synthesis gas for production of methane or liquid fuels. Research in medium-Btu gasification has focused on using the high reactivity of biomass to reduce or eliminate the requirement for oxygen in the gasifier. Research has also centered on determining the technical feasibility of producing synthesis gas for production of high-value liquid and gaseous fuels. In addition to the primary emphasis on medium-Btu gasification research, the Biomass Thermochemical Conversion

Program also sponsors a small amount of research on low-Btu gasifiers to improve overall reliability and acceptability of such systems. This research is aimed at methods of increasing gasifier performance and improving product gas cleanup.

The gasification research projects sponsored by the Biomass Thermochemical Conversion Program are shown in Figure 8. A brief description of each project and a discussion of progress during FY 1984 are given below.

FIGURE 8. Gasification Research Projects

Medium-Btu Gasifiers

BATTELLE-COLUMBUS LABORATORIES (BCL), Columbus, Ohio, is conducting research to determine the feasibility of using a dual bed, entrained gasifier to produce a medium-Btu fuel gas. The concept provides for indirect heating of the gasifier by circulating a low density, hot incandescent sand from a combustor to the gasifier, eliminating the need for using purified oxygen. As shown in Figure 9, the entrained sand and any char leaving the gasifier is separated from the product gas in a cyclone. Both the sand and char are

transferred to an entrained bed combustor where the char is burned with air. The sand is heated to a high temperature and recirculated back to the gasifier. The apparatus is shown photographically in Figure 11; the feeder is in the foreground with the insulated gasifier behind it.

FIGURE 9. Schematic Diagram of Battelle-Columbus Gasifier

In previous research, BCL successfully produced a medium-Btu fuel gas with a heating value of about 475 Btu/scf using both wood chips and coarsely shredded bark. As shown in Figure 10, this heating value did not vary signifi-

FIGURE 10. Heating Value of Product Gas is Independent of Feedstock Moisture Content

FIGURE 11. View of Battelle-Columbus Gasifier

cantly for feedstocks containing from 8% to 40% moisture on a wet basis. Gasifier throughputs of up to 1800 lb/hr/ft² were achieved.

In 1984, BCL successfully operated the 10-in. gasifier for extended periods up to 72 hours of continuous operation. During the extended runs, system components operated as planned. The tests established that the results from the extended, steady-state operation closely matched those from shorter duration trials. The extended runs also allowed better closure of the mass balance, particularly in the area of quantifying liquid effluents. BCL also completed tests on gasification of hogged fuel from stumps. The hogged fuel gasification tests were very similar to previous tests using debarked wood chips.

THE UNIVERSITY OF MISSOURI, Rolla, Missouri, is investigating the technical feasibility of using metal fire-tubes to provide heat indirectly to a fluidized bed gasifier. In the conceptual design, a portion of the feedstock or product gas would be burned to provide heat for the fire-tube heat exchanger. The concept eliminates the need for pure oxygen in the gasifier. The University has constructed a 20-in. fluidized bed gasifier with an internal fire-tube heat exchanger. The configuration selected for actual testing uses thirty 1-in. diameter U-tubes spaced on a 2-in. pitch. One view of the reactor is shown in Figure 12. The system has been operated at feed rates up to 400 lb/hr (10% moisture wood) and temperatures up to 1365°F.

During 1984, the University of Missouri has been conducting extensive tests to characterize performance of the gasifier. Based on initial experiments, modifications were made to the fire-tube bundle which resulted in greatly improved structural integrity and heat exchanger performance. Heat transfer rates in the modified reactor were about 16 Btu/hr-ft²-°F, an improvement of over 40% from the previous configuration. The new tube bundle has now been operated a cumulative total of over 1000 hours.

THE INSTITUTE OF GAS TECHNOLOGY (IGT), Chicago, Illinois, is conducting research to determine the actual oxygen requirements for gasifying biomass to produce a medium-Btu gas. A 12-in. diameter fluidized bed research gasifier

FIGURE 12. View of Gasifier at University of Missouri-Rolla

was constructed to explore the effects of pressure (up to 500 psia), reactor bed height, feed positions, feedstock type, and temperature on product gas yield and composition. The gasifier is shown schematically in Figure 13.

FIGURE 13. Schematic Diagram of Gasifier at Institute of Gas Technology

During 1984, IGT completed shakedown operation of the gasifier and began regular experimental operation. Wood feedstock throughputs of about 1000 lb/hr/ft² were achieved. At these feed rates, a pressure of 325 psia, and a temperature of about 1500°F, the total carbon conversion to gas exceeded 88%. Under these conditions, steam requirements were in the range of 0.5 to 0.8 lb/lb wood. Perhaps most important, the oxygen requirements over a variety of conditions were found to be relatively low. Under the conditions above, the oxygen requirement was 0.21 to 0.34 lb/lb wood. This promising result has favorable impact on projected costs for synthesis gas production.

Medium-Btu Gasification Research

PACIFIC NORTHWEST LABORATORY (PNL), Richland, Washington, is conducting research on the effect which catalysts can have on raw gas composition in medium-Btu biomass gasification processes. The primary goal of the research is to determine the technical feasibility of producing tailored synthesis gas in a medium-Btu gasifier. Synthesis gases for the production of high-value

liquid and gaseous fuels require relatively pure mixtures of hydrogen and carbon monoxide with specific molar ratios. Research at PNL is examining the feasibility of producing synthesis gases tailored to specific needs directly in the gasifier. In addition, PNL is examining the technical feasibility of using catalysts to upgrade medium-Btu fuel gases by eliminating tar components in the gas stream.

During 1984, PNL designed and constructed a bench-scale fluidized bed test reactor system in order to test catalyst lifetimes. The reactor is shown schematically in Figure 14. The reactor has been operated both with the catalyst in the primary fluidized bed where gasification occurs and with the catalyst in a secondary fluidized bed immediately downstream. Catalysts of Ni/Cu/Mo on silica-alumina have been found which retain activity for synthesis gas production for extended periods in both reactor configurations. Catalysts in the secondary fluidized bed are particularly effective in eliminating tars and other unwanted hydrocarbons in the gas stream.

FIGURE 14. Bench-Scale Fluidized Bed Gasifier at Pacific Northwest Laboratory

TEXAS TECH UNIVERSITY, Lubbock, Texas, is investigating the technical feasibility of enhancing the radiant heat transfer capabilities of indirectly

heated fluidized bed gasifiers. The concept uses ceramic heat exchanger fire-tubes doped with rare-earth metals to match the wavelength of the heat radiated by the tubes to the absorption wavelengths of the biomass.

During 1984, experimental and theoretical modeling studies of radiant heat transfer in fluidized beds were completed. A radiant thermogravimetric analysis unit was also placed into service. Based on these studies, the preferred geometric orientation for radiant tubes in a fluidized bed was determined. In the preferred orientation, the fire-tubes are in ranks which intersect the reactor walls at 45 degree angles, resulting in the most stable fluidized bed in the best solids mixing. The research was moved to University of Nebraska-Lincoln late in 1984 when the principal investigator changed institutions.

PACIFIC NORTHWEST LABORATORY, Richland, Washington, is also conducting research on the gasification of high moisture biomass feedstocks. The concept under consideration uses a nickel/carbonate catalyst at moderate temperatures (400-450°C) and high pressures (approx. 4000 psi) to gasify biomass to a methane-rich product. High moisture feedstocks up to about 90% moisture such as grasses, food processing wastes, and aquatic species can be thermally gasified in this manner.

During 1985, preliminary experiments were initiated to test the technical feasibility of this concept. At 400°C, product yields were dependent on the feedstock species. At 450°C, however, product yields were uniform with about 23% methane, 35% hydrogen, and 39% CO₂ over a wide range of feedstocks including potato waste, sunflowers, and napier grass. At 450°C, overall carbon conversion to gaseous products exceeded 90% for several feedstocks. Continuing work in 1985 will further explore this concept.

Low-Btu Gasification Research

In addition to the primary goal of producing a technology data base for medium-Btu gasification, the Biomass Thermochemical Conversion Program conducted research on low-Btu gasification in fiscal year 1984. The main goal of this research has been to improve the overall reliability of this technology option.

THE UNIVERSITY OF FLORIDA, Gainesville, Florida, conducted research to enhance the performance of engines fueled with producer gas. Project goals are to evaluate the use of positive displacement and turbine superchargers for increasing the power output of engines operated on low-Btu gas and to evaluate microprocessors as means of automatically adjusting air-fuel mixtures in such engines. The power output from both spark ignition and diesel engines operated on producer gas are being measured and compared with power output achieved using conventional fuels. This performance is also being measured against that of the same engines fitted with positive displacement blowers and turbocharging systems. The increased energy density in the fuel gas is expected to enhance engine performance. Concurrent with these experiments, tests will be conducted to evaluate the performance of combustion sensors coupled to microprocessors for adjusting air-fuel mixtures on the engines.

CAL RECOVERY SYSTEMS, INCORPORATED, Richmond, California, completed work to identify ways of improving the operation of biomass gasifiers/engine systems. The research examined the effect of different biomass fuel gas/conventional liquid fuel ratios on engine performance as a function of total energy input, engine load, compression ratio, and other variables. In the engine testing work, Cal Recovery found that producer gas caused substantial ignition and burning delays in both diesel and spark ignition engines. In diesel engines, the effect could be minimized by advancing the injection timing. Spark ignition engines were adjusted by advancing the spark timing over that used for gasoline-only operation.

ROCKY CREEK FARM GASOGENS, INCORPORATED, LaCrosse, Florida, conducted research on methods of cleaning gases from low-Btu gasifiers for engine use. This research used a downdraft gasifier mounted on a 40-hp John Deere tractor for a combination of laboratory research and field testing. Laboratory research included particulate measurements as a function of gas cleanup methods, fuel characteristics, and other factors. Field testing of the unit was also performed to provide operational data on the acceptability of the producer gas-fueled tractor, including identification of best gas cleanup methods, operator-associated problems, and related factors. The tractor performance with the gasifier was found to be acceptable under most conditions. Particulates in the gas less than 5 microns in size were found to be completely

burned in the engine, while larger particulates required filtering. Simple fiberglass batts were found to be reliable and inexpensive filters. A final report will be submitted in 1985.

LIQUID FUELS TECHNOLOGY

The Biomass Thermochemical Conversion Program is also conducting research on the production of liquid fuels from biomass. Liquid fuels have several advantages over the biomass resource itself. Perhaps most important, liquid fuels have a higher energy density. This allows the liquid product to be transported more economically and to be more easily stored. Liquid fuels also match existing end-use patterns, particularly by the transportation sector. The goal of the liquid fuels research sponsored by the Biomass Thermochemical Conversion Program is to provide the technology base for producing economical liquids that are compatible with existing hydrocarbon fuels. To meet this goal, the program is conducting research directed at:

- identifying reaction pathways and methods for producing high-value liquid fuels
- improving yields and quality of liquid fuels
- producing economically competitive fuels.

As shown in Figure 15, the research is divided into two primary areas including pyrolysis and direct liquefaction. The differences in these approaches make it possible to generate a variety of fuels ranging from fuel oil substitutes to olefinic/aromatic hydrocarbons. The ability to produce a variety of fuels is important in meeting the wide range of demands from the liquid fuel market. These two research areas and the specific projects in each are described in detail below.

Pyrolysis

Pyrolysis refers to the heating of biomass in the absence of air. Traditionally, pyrolysis has been used to produce charcoal. Conventional pyrolysis typically produces about one-third each gases, pyrolysis oils, and char. The process is inefficient because large quantities of low-value liquids and gases are formed in addition to desired solid products. Batchwise,

FIGURE 15. Liquid Fuels Research Projects

often primitive, conversion units have also added to the inefficiency of conventional pyrolysis processes.

In recent years, the concept of rapid pyrolysis has emerged as a promising alternative for producing liquid fuels. Using rapid heating rates, yields of gases and liquids as high as 95% can be produced. These products may contain up to about 20% high-value olefinic products such as ethylene and BTX (benzene, toluene, and xylene), and are potentially useful as fuels and octane enhancers.

The pyrolysis research sponsored by the Thermochemical Conversion Program is directed toward capitalizing on these results by:

- investigating extremely fast pyrolysis to maximize yields of high-value olefins and aromatics
- improving the yields of fast pyrolysis by conducting the reactions in atmospheres of reactive gases
- using fast pyrolysis to produce high yields of low-cost fuel oil substitutes.

Four research projects are currently being conducted in fast pyrolysis.

SOLAR ENERGY RESEARCH INSTITUTE (SERI), Golden, Colorado, is conducting two projects to investigate the fast pyrolysis of biomass. In the first project, basic research examining the mechanisms occurring in fast pyrolysis is underway. Using a molecular beam mass spectrometer, a detailed picture of the individual, sequential reaction steps occurring during fast pyrolysis is being developed by measuring the change in product spectrum occurring during millisecond intervals. Although there are many possible mechanisms for producing low-value char and tars, the production of high-value products appears to be limited to conditions of high heating rates and relatively high temperatures (500 to 700°C). Representative competing pyrolysis reaction pathways are shown in Figure 16.

FIGURE 16. Reactive Pathways for Biomass Pyrolysis

During 1984, SERI placed emphasis on analysis of lignin reactions during pyrolysis and on the secondary cracking of biomass-derived vapors. The studies are yielding a detailed view of the sequential reaction pathways which are occurring both in the initial formation of the vapors and their secondary cracking of those vapors. SERI also has been developing a new computerized data system to aid in the collection and processing of the mass spectrometer instrumentation.

The second project at SERI is investigating the use of a unique ablative reactor for fast pyrolysis. The goal of this research is to determine detailed information about heat fluxes needed for rapid pyrolysis and to investigate fundamental reaction mechanisms. In ablative pyrolysis of biomass, particles are heated by being forced against a hot reactor wall. Contact of the biomass with the reactor surface converts the biomass into a liquid layer, which is subsequently vaporized. Heatup rates as high as $500,000^{\circ}\text{C}/\text{sec}$ can be obtained at the sample surface. A schematic of the reactor system is shown in Figure 17. The initial products formed in the reactor section are primary pyrolysis vapors which can be condensed as pyrolysis oils at yields of about 60%. The primary tars can also undergo secondary cracking in the vapor cracker to form high-value products such as benzene, toluene, xylene and ethylene, as well as carbon monoxide and hydrogen which could potentially be used as synthesis gas.

FIGURE 17. Ablative Biomass Pyrolysis Reactor at Solar Energy Research Institute

During 1984, SERI completed extensive experimental work which confirmed that a temperature window exists for maximum ablative pyrolysis efficiency. This effect had been predicted in earlier theoretical modeling studies at SERI. By lowering the temperature of the reactor wall from 750°C to about 650°C , improved reactor performance was obtained. At the higher temperatures, the thin layer of biomass liquid formed by contact with the hot wall underwent secondary reaction before it could completely vaporize. The secondary products were converted to carbon at the wall which disrupted both the heat flux and the flow of the wood feed. Based on this information, it was felt that a liquid metal heat exchanger reactor which had previously been contemplated

would not be necessary. Instead, a radio frequency induction reactor is nearing completion and will be tested in 1985.

Research at BROOKHAVEN NATIONAL LABORATORY, Upton, New York, is investigating the effect of conducting rapid pyrolysis in the presence of reactive atmospheres. Using a bench-scale, entrained downflow reactor, biomass is pyrolyzed at pressures of 50 to 500 psi and temperatures of 800 to 1100°C. Under these conditions, the yields of high-value products such as ethylene, benzene, toluene, and xylene can be up to about 2.5 times greater than those from otherwise identical conditions where an inert gas (i.e., helium) is used. The presence of the methane can therefore lead to a significantly upgraded product spectrum at relatively moderate pyrolysis heat-up rates.

During 1984, research focused on quantifying the effect of methane on the biomass pyrolysis and understanding the reaction mechanisms. As shown in Figure 18, the maximum ethylene, BTX, and total hydrocarbon yields from pine wood reacting in methane are achieved at about 1000°C. The yields drop at either higher or lower temperatures. At 1000°C, the yield of BTX in the methane atmosphere is about 2.5 times that observed in helium, and the total hydrocarbon yield is about double. Experiments have suggested that the effect

FIGURE 18. Schematic Diagram of Pyrolysis Reactor at Brookhaven National Laboratory

may arise from the formation of free radicals from the biomass which subsequently react with methane. Further exploration of these reaction mechanisms will be conducted in 1985.

GEORGIA TECH RESEARCH CORPORATION, Atlanta, Georgia, is conducting research on rapid pyrolysis of biomass with the goal of producing low cost liquid products that could potentially be used as fuel oil substitutes. The research makes use of an entrained flow pyrolyzer where biomass is converted primarily to liquid products under conditions of moderate heating rates and temperatures. The system, as shown in Figure 19, consists of an entrained, upflow reactor and an oil recovery stream that allows partial on-stream fractionation of the product. A photo of the unit is shown in Figure 20.

During 1984, Georgia Tech Research Corporation performed experimental research which established the interdependence of the reaction temperature and residence time on pyrolysis oil yield. Testing over temperatures from 400 to 550°C gave mass yields of moisture-free oil ranging from 31 to 53%. The

FIGURE 19. Schematic Diagram of Entrained-Flow Pyrolysis Reactor at Georgia Tech Research Corporation

entrained flow reactor was also modified to allow shorter residence times, which is expected to further increase product yields. The reactor was modified from 8-in. to 6-in. allowing residence times to be cut by nearly half. Operation of the modified reactor is expected in 1985.

FIGURE 20. View of Georgia Tech Research Corporation Pyrolysis Reactor

Direct Liquefaction

Direct liquefaction research, at this time, is based primarily on a concept first proposed by the Pittsburgh Energy Research Center (PERC). In this concept, biomass is mixed with recycled wood oil and sodium carbonate catalyst along with a H_2/CO reducing gas. The mixture is injected into a high-pressure vessel (3000 psi) and heated to about $350^{\circ}C$. The product stream is cooled and flashed into a pressure let-down vessel. The oil phase product is withdrawn and part of it is recycled for use as slurry medium.

During 1981, the PERC process was tested in a DOE research facility located at Albany, Oregon. These tests confirmed the technical feasibility of this approach. Over 11,000 pounds of oil resembling No. 6 fuel oil were produced in one run alone. However, the results indicated that the process is not now economically competitive, partly because of the large recycle oil requirement. The Thermochemical Conversion Program is attempting to improve the competitiveness of direct liquefaction by:

- improving the economics of direct liquefaction through the use of increased feedstock slurry concentrations
- improving product quality by reducing oxygen content and molecular weight.

THE UNIVERSITY OF ARIZONA, Tucson, Arizona, is conducting research on an advanced concept for direct liquefaction that would use very concentrated biomass slurries. The goal of this work has been to use a polymer extruder as a slurry feeding/pumping device. The modified extruder/feeder system is capable of handling slurries as concentrated as 60% wood solids in biomass oil. Conventional systems, by comparison, typically cannot handle slurries containing over about 20% wood. During 1984, the University of Arizona designed and constructed an integrated extruder/static mixer liquefaction system as shown in Figure 21. The static mixer is expected to allow adequate mixing and agitation of the viscous slurries. Construction of the unit is nearing completion and shakedown operation is expected in early 1985.

FIGURE 21. Schematic Diagram of Direct Liquefaction Unit at University of Arizona

PACIFIC NORTHWEST LABORATORY, Richland, Washington, is conducting research on the characterization and upgrading of both pyrolysis and direct liquefaction oils. Characterization studies show that there are significant differences between the pyrolysis and the direct liquefaction oils. As shown in Table 1, pyrolysis oils contain more oxygen and are less viscous than the liquefaction products. The liquefaction products contain large quantities of phenolic compounds while the pyrolysis oils have large concentrations of organic acids. These differences directly impact the methods for upgrading these products.

TABLE 1. Biomass Liquefaction Products Comparative Analytical Data

Elemental Analysis (MAF)	Direct Liquefaction Oil (PERC-Albany TR12)	Fast Pyrolysis Oil (Georgia Tech #11)
Carbon	81.0%	59.2%
Hydrogen	10.2%	7.0%
Oxygen	8.8%	33.8%
Nitrogen	0.1%	0.1%
Sulfur	1.50	1.41
Moisture and Heating Value		
% H ₂ O	7.3	19.7
raw HHV	14,200 Btu/lb	7,950 Btu/lb
MAF HHV	15,300 Btu/lb	9,800 Btu/lb
Other Properties		
viscosity cps @ 40°C	400,000	62
density g/ml @ 23°C	1.14	1.24
pourpoint	27°C	-15°C

During 1984, the oils from several liquefaction and pyrolysis processes were analyzed in detail. The oils show differences in characteristics based both on the temperature/residence time history as well feedstock characteristics (such as hard or soft wood). This information will be used in 1985 to hydrotreat the less stable pyrolysis oils.

DIRECT COMBUSTION TECHNOLOGY

Direct combustion of biomass feedstocks, particularly wood, is already widely practiced by the private sector, especially in the forest products industry. Prior to the introduction of extensive natural gas distribution systems and cheap imported crude oil following World War II, many forest products companies utilized wood wastes from their operations to supply a large portion of their energy needs. In the current era of uncertain energy costs, there is widespread interest in returning to self-sufficiency in fuel supplies. Many types of direct combustion equipment, such as wood-fired boilers and various types of burners, are commercially available for this purpose.

Therefore, direct combustion projects funded by the Biomass Thermochemical Conversion Program have focused on unique, innovative combustion systems or special issues involved in combusting biomass fuels.

The Biomass Thermochemical Conversion Program is currently sponsoring direct combustion research that is focused on determining the technical feasibility of converting the heat released from direct combustion directly into mechanical power. By directly producing mechanical power without the use of an intermediate working fluid such as steam in a boiler/steam turbine system, high conversion efficiencies can be realized. In addition, costs associated with the working fluid, such as boilers and condensers, are eliminated, allowing small engines to operate economically. The Biomass Thermochemical Conversion Program is also sponsoring research on the fundamental aspects of biomass combustion. This research is aimed at increasing our understanding of basic combustion rates and mechanisms, to both improve combustion efficiencies and lower undesired combustion emissions. As shown in

Figure 22, the Program sponsored two biomass direct combustion projects during 1984.

FIGURE 22. Direct Combustion Research Projects

AEROSPACE RESEARCH CORPORATION, Roanoke, Virginia, is conducting research on a directly-fired gas turbine generating system using wood feedstock. The objective of this project is to determine whether combustion gases from wood can be sufficiently cleaned using a series of cyclones to power gas turbines dependably and economically. Hot combustion gases from a pressurized wood-fired suspension burner are passed through a series of cyclones to remove particulate matter and are injected directly into a gas turbine. A schematic diagram of this concept is shown in Figure 23. In previous trials using a 375-kW combustor/gas turbine, over 500 hours of operation were completed with no

FIGURE 23. Schematic Diagram of Combustor/Gas Turbine at Aerospace Research Corporation

significant signs of erosion or corrosion to the turbine blades. Tests showed that particulate loading in the 375-kW system was very low.

During 1984, Aerospace Research Corporation completed construction of a 3-MW combustor/gas turbine with electrical generator. A photograph of the complete 3-MW unit is shown in Figure 24, and a close-up of the turbine and generator system is shown in Figure 25. The unit successfully underwent initial shakedown operation in September 1984. During the shakedown operation, all system components were tested. Turbine speeds up to about 25% of design maximum were achieved, and particulate measurements at the turbine inlet were made. The particulate loading was measured at about 0.030 grains per dry standard cubic foot with 86% smaller than 0.55 microns. This particulate level is acceptable for general gas turbine applications. Even lower particulate levels should be present when full speed turbine operation is attained due to higher cyclone efficiencies at higher gas velocities. The unit is currently being moved to Red Boiling Springs, Tennessee, where it will undergo long-term testing while generating electrical power to be sold to the Tennessee Valley Authority. Over 80% of the funds for the 3000-kW unit are being provided by the private sector. The Allison Division of General Motors is donating the gas turbine for the project. In 1984, Department of Energy funding for this project was provided jointly by the Biomass Thermochemical Conversion Program and the Southeastern Regional Biomass Energy Program which is managed by the Tennessee Valley Authority.

JET PROPULSION LABORATORY, Pasadena, California, conducted basic research on biomass combustion reactions. This work is developing a predictive model that correlates combustion behavior with wood particle size, type, moisture content, and heating value. Experimental verification of the predictive model is also being performed. In addition, the research will explore the effect of additives such as alkali salts on combustion behavior. The results of this research will be used to develop a more complete fundamental understanding of combustion reactions. By applying this knowledge, combustion processes that are both more complete and more environmentally acceptable should be possible.

FIGURE 24. View of Completed 3-MW Combustor/Gas Turbine System

FIGURE 25. View of Gas Turbine and Generator System

PROGRAM SUPPORT ACTIVITIES

During 1984, the Biomass Thermochemical Conversion Program sponsored additional research activities with the goal of supporting major program elements. This research includes technoeconomic evaluation of candidate processes, a review of DOE sponsored biomass gasification technology, examination of methods for reducing aqueous and tar effluents in biomass gasification systems, and studies of using biomass/coal/MSW briquets in conversion systems. Program support research is shown in Figure 26.

FIGURE 26. Program Support Research Projects

SCIENCE APPLICATIONS INTERNATIONAL CORPORATION (SAIC), Arlington, Virginia, conducted engineering and economic studies to assess advanced biomass conversion concepts. During 1984, SAIC completed analyses on both wood-fired gas turbine systems for electric power generation and a flash methanopyrolysis concept for production of liquid fuels. Four alternative versions of the Aerospace wood-fired gas turbine system were examined for electricity and heat production. For plants consisting of four 3-MW gas turbine/generator modules, total capital costs were estimated to be about \$6-7 million, depending on whether heat recuperators were used. Electricity costs for the 4-turbine grouping ranged from about 3.2 to 3.7 cents per kWh for wood

feedstock at \$15/dry ton depending on whether public utility or private financing was used. The private industry case included a return on equity of 15%.

SAIC also analyzed six variations of a concept for producing liquid fuels by the pyrolysis of biomass in a reactive atmosphere of methane. The result, based on preliminary experimental data from Brookhaven National Laboratory, indicate that this concept may have good economic potential.

GEORGIA TECH RESEARCH CORPORATION, Atlanta, Georgia, is conducting research to reduce tar and aqueous effluents in biomass gasification systems. The concept uses an external combustor to burn tars produced in an updraft gasifier. The hot combustion products will then be used to vaporize a portion of the aqueous effluent. The resulting mixture is used as a moderator gas in the gasifier, thus eliminating or reducing the need for a separate steam boiler. The concept also provides for destruction of the difficult-to-handle tars that otherwise would present disposal problems. During 1984, Georgia Tech Research Corporation completed construction of a system coupled to their gasifier that will simulate the injection of the tar combustion products and steam into an updraft gasifier. A predictive model has also been developed which will be used to estimate the effects of displacing part of the airflow through the gasifier with the moderator gas produced in the combustor. The results are expected to provide important information for designing the tar combustor/wastewater vaporizer system to be tested later in the program.

PACIFIC NORTHWEST LABORATORY (PNL), Richland, Washington, performed an evaluation of gas stream cleanup technologies with specific emphasis on tar and particulate removal. The overall goal of this work is to identify potential problem areas and gaps in the technology which could impede development of biomass gasification. During 1984, PNL completed a state-of-the-art review of gas cleaning technology as it relates to biomass gasification. The report contains an overview of biomass gasification contaminants, end uses for biomass gas, and a review of current gas cleanup technology. The report concludes that present particle scrubbing technology is probably adequate to deal with biomass gas requirements, but that there are many uncertainties in the area of tar removal. The tars in biomass systems are different chemically

and physically from coal tars, and methods of collection and disposal may need additional research.

AETA CORPORATION, Dover, New Hampshire, is conducting a comprehensive review of biomass gasification research sponsored by the U. S. Department of Energy. Eight projects were identified for review, and a literature search plus compilation of summary data sheets were completed. Technoeconomic analyses of the candidate processes are now being undertaken to determine what technical and economic issues remain to be solved before the transfer of the technology to the private sector can be successful.

DYNECOLOGY INCORPORATED, Harrison, New York, completed research to determine the feasibility of using biomass/coal/sewage sludge briquets in gasification systems. The research showed that the concept has both technical and economic potential. Structurally sound briquets of various coal/cellulosic materials could readily be made on commercially available equipment. Gasification tests of these briquets were also made using a slagging fixed bed gasifier. The pelleted mixture gasified cleanly without agglomeration. Dynecology also performed a preliminary technoeconomic analysis for gasification of these type of briquets. The analysis indicated that a 120 ton/day briqueting and gasification plant could be built for about \$14 million and could cost \$3.1 million per year to operate. Depending on tipping fees for the sewage sludge, rates of return exceeding 35% could potentially be realized according to the analysis.

Additional Information

Detailed descriptions of all the research and development projects funded by the Biomass Thermochemical Conversion Program are given in the Proceedings of the 16th Biomass Thermochemical Conversion Contractors' Meeting, August 1984. This document, CONF-8405157, is available from the National Technical Information Service, United States Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161. Additional information is also available from the publications listed in the Appendix.

APPENDIX

BIOMASS THERMOCHEMICAL CONVERSION PROGRAM

Project Title: Development of Wood as an Alternative Fuel for Gas Turbines - Aerospace Research Corporation

Hamrick, J. T. "The Design and Development of a Wood Burning Gas Turbine." High Temperature Technology, Vol. 2 No. 1, February 1984.

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Hamrick, J. T. "Development of Wood-Burning Gas Turbine Systems." Modern Power Systems, Vol. 4 No. 6, June 1984.

Hamrick, J. T. "High Temperature Wood Burning Gas Turbine." Presented at the Symposium entitled "Pyrolysis, Combustion and Gasification of Biomass" at the 187th National Meeting of the American Chemical Society in Philadelphia, Pennsylvania, 26-31 August 1984.

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Layne, R. "This Gas Turbine Burns Sawdust." Popular Science, November 1984.

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Project Title: Review of Biomass Gasification Research Sponsored by the U. S. Department of Energy - AETA Corporation

Master, D. B. "Technology Transfer of Biomass Based Energy Processes." In Proceedings of the 16th Biomass Thermochemical Conversion Contractors' Meeting, Portland, Oregon, 8-9 May 1984. CONF-8405157 (NTIS).

Project Title: Advanced Biomass Direct Liquefaction Extruder-Feeder Reactor Systems - University of Arizona

Ghoddoussi, M. G. "Solvolysis of Biomass at Elevated Temperatures." Master of Science Thesis, University of Arizona, December 1983.

Homaidan, A. "Modeling of Extruder-Feeder for Biomass Concentrated Slurries." Master of Science Thesis, University of Arizona, May 1984.

Khan, M. B. "Gas Dispersion in Viscous Non-Newtonian Fluids Using an Extruder-Feeder." Master of Science Thesis, University of Arizona, August 1984.

Lezzar, A. "Effects of Void Volume on the Friction and Rheology of Concentrated Slurries," Master of Science Thesis, University of Arizona, December 1983.

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White, D. H. "Development of Extruder-Feeder Biomass Liquefaction System." In Proceedings of the 16th Biomass Thermochemical Conversion Contractors' Meeting, Portland, Oregon, 8-9 May 1984. CONF-8405157 (NTIS).

Project Title: Engineering Analysis of Biomass Gasifier Product Gas Cleaning Technology - Pacific Northwest Laboratory

None.

Project Title: Conversion of Forest Residues to a Methane-Rich Gas in a High Throughput Gasifier - Battelle Columbus Laboratories

Appelbaum, H. R., M. A. Paisley, and H. F. Feldmann. "Computer Modeling of the Battelle High Throughput Biomass Gasification System." 7th Energy Sources Technology Conference, New Orleans, Louisiana, 12-16 February 1984.

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