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Biomass Thermochemical Conversion Program 1985 Annual Report

January 1986

G. F. Schiefelbein
D. J. Stevens
M. A. Gerber

Biomass Program Office

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
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BIOMASS THERMOCHEMICAL CONVERSION PROGRAM 1985 ANNUAL REPORT

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Prepared for
the U.S. Department of Energy
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Pacific Northwest Laboratory
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--about 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. In addition, biomass is the only renewable energy technology capable of addressing the future need for transportation fuels.

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 Biofuels and Municipal Waste Technology Division, Office of Renewable Technologies. 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 1985.

PROGRAM OBJECTIVE AND RESEARCH AREAS

The objective of the Biomass Thermochemical Conversion Program is to generate a base of scientific data and conversion process information that will lead to establishment of cost-effective processes for converting biomass resources into clean fuels. To accomplish this objective, the Thermochemical Conversion Program is sponsoring research activities in the following 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 1985 are summarized below.

MAJOR ACCOMPLISHMENTS IN 1985

The Biomass Thermochemical Conversion Program made major progress in 1985 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 basic level in understanding the reaction behavior involved in converting biomass feedstocks. Accomplishments of the Biomass Thermochemical Conversion Program during FY85 include:

- Successful Completion of Initial Extended Term Tests for Three Medium-Btu Biomass Gasifiers. Researchers at Battelle Columbus Laboratory (BCL), Institute of Gas Technology (IGT), and University of Missouri-Rolla (UMR) successfully completed initial extended-duration tests of medium-Btu biomass gasifiers at each of those sites. The length of tests ranged from approximately three days of continuous operation at IGT to about five days at UMR. The tests are very important in developing process data such as accurate mass and energy balances under continuous, steady state operating conditions. The test results also give important information on process reliability and other operational considerations.
- Completion of Comprehensive Data Packages for Four Biomass Medium-Btu Gasifiers. Comprehensive data packages for gasifiers at Battelle Columbus Laboratory, Institute of Gas Technology, and University of Missouri-Rolla were submitted to DOE in FY85. The data packages summarize the current state-ofthe-art for each of these gasification concepts. Included in the packages are process descriptions, recent experimental data, and other information relating to the various gasifier concepts. The data packages were prepared for DOE in response to a request for information relating to a possible scale-up activity being considered by DOE. A fourth data

package on a gasifier operated by SynGas, Inc. under contract to Solar Energy Research Institute is expected to be submitted in early FY86.

- Determination That High Moisture Biomass Feedstocks can be Successfully Gasified at Low Temperature. Pacific Northwest Laboratory performed preliminary experiments which showed high moisture biomass feedstocks can be thermochemically gasified at low temperatures (~ 400°C). The concept converts biomass in a aqueous slurry to a methane-rich gas composed almost entirely of CH_4, H_2, and CO_2. The product gas could be used directly as a medium-Btu fuel gas or as a high-Btu gas following CO_2 removal. The concept exhibits high carbon conversion efficiencies for many herbaceous and woody feedstocks. The experimental results indicate that thermal conversion techniques may be suitable for most biomass feedstocks including very moist ones.

- Operation of an Advanced Biomass Liquefaction Reactor Capable of Handling Concentrated, Viscous Biomass Slurries. The University of Arizona successfully initiated testing of an advanced concept reactor for producing biocrude liquids. The concept uses an extruder/static mixer reactor to convert viscous, concentrated slurries of biomass into biocrude oil. Initial testing has shown that biocrude oil with low oxygen content can be made from slurries up to 60% biomass by weight. This reduces the recycle oil/feedstock ratio from about 10:1 in previous systems to as low as 1:1 with the present system. Reducing this ratio while maintaining product quality should substantially improve process economics.

- Preliminary Determination of Methods for Upgrading Biocrude Oils to Gasoline-Compatible Fuels. Pacific Northwest Laboratory successfully completed preliminary experiments which identified routes for upgrading biocrude liquefaction oils to gasoline-like hydrocarbons. One-step catalytic hydrotreating was found to be successful for biocrude oils produced in high pressure liquefaction systems. For pyrolytic oils, a two-step process including initial stabilization and subsequent upgrading appears to be feasible. In both cases, the crude oils are upgraded at high yields (>90% carbon conversion) to liquid hydrocarbons in the gasoline boiling range. Oxygen in the biocrude oils was essentially eliminated, and a true hydrocarbon fuel was produced.

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INTRODUCTION

Biomass represents an important but underutilized energy resource in the United States. In 1981, for example, it has been estimated[a] that biomass contributed about 3.5% of the nation's energy supply, approximately equivalent with nuclear energy which supplied 3.8% that year. With proper resource management and the development of efficient conversion processes, the Office of Technology Assessment has estimated[b] the potential contribution of biomass to the U.S. energy supply could range as high as 17 quadrillion Btu per year, about 20% of current U.S. energy consumption. Similarly, the Energy Research Advisory Board (ERAB) has estimated[c] that biomass could potentially supply the nation with about 10 quadrillion Btu by the year 2000.

A wide variety of biomass resources such as wood and forest product residues, grasses, agricultural crops and their residues, and animal wastes can be used as energy feedstocks. As an abundant, renewable, domestic energy resource, biomass can help the United States reduce its dependence on imported oil and natural gas. In addition, biomass is the only renewable energy technology capable of addressing the need for liquid transportation fuels[d].

The U.S. Department of Energy (DOE) is encouraging increased utilization of biomass resources through research projects sponsored by its Biofuels and Municipal Waste Technology Division, Office of Renewable Technologies. Pacific Northwest Laboratory (PNL)[e] has been designated the Field Management Office

(a) Haggin, J. and J. H. Kriegr. Chem. and Eng. News, p. 28, March 14, 1984.

(b) Office of Technology Assessment. 1980. Energy from Biological Processes. Vol. I, Biomass Resource Base, U.S. Governmental Printing Office, Washington, D.C.

(c) 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.

(d) Collins, P. Energy From Biomass: Building on a Generic Technology Base. November 27, 1984, p. 5. ANL/CNSV-TM-157.

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

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 including its organization, underlying objective and goal, rationale, and approach. The Program subcontracted research activities during fiscal year 1985 are then documented. Recent publications 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 Biofuels and Municipal Waste Technology Division is shown in Figure 1.

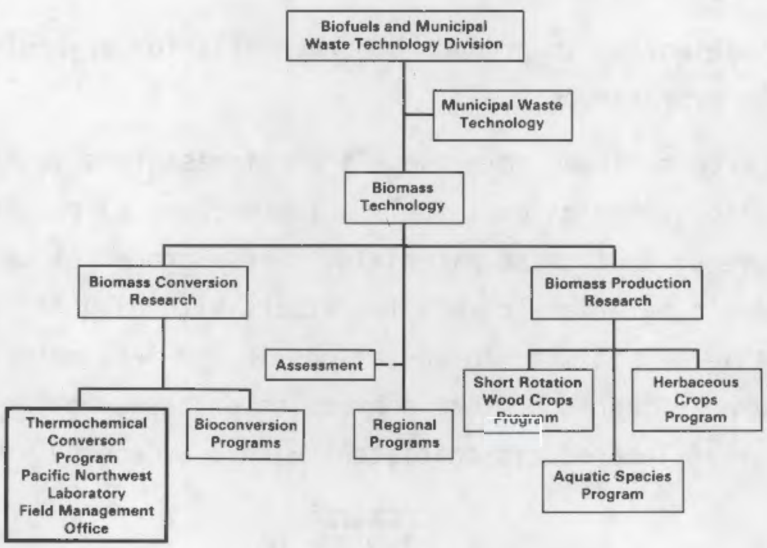

FIGURE 1. Relationship of Biomass Thermochemical Conversion Program to Biofuels and Municipal Waste Technology Division Organization

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-, intermediate-, or high-energy fuel gas
- gasification to produce synthesis gas for the production of high-value liquid and gaseous fuels
- direct liquefaction to produce biocrude oils for upgrading into gasoline compatible hydrocarbon fuels.

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 consistent with U.S. energy use patterns.

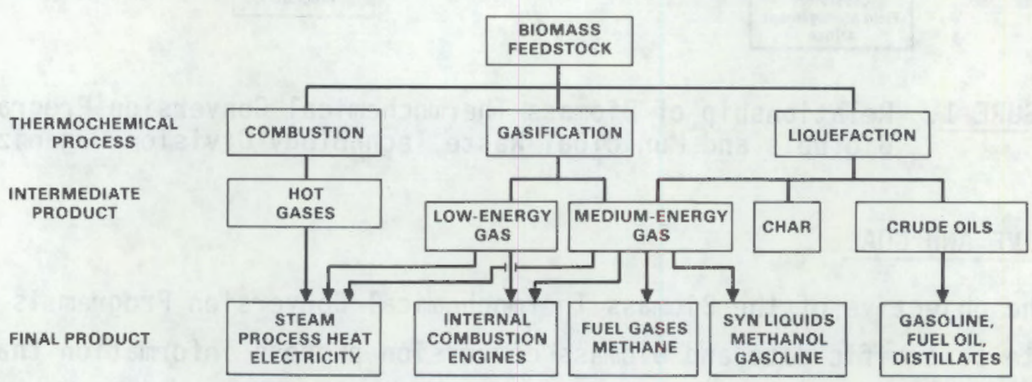

FIGURE 2. Thermochemical Conversion Can Provide a Wide Spectrum of Products

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.

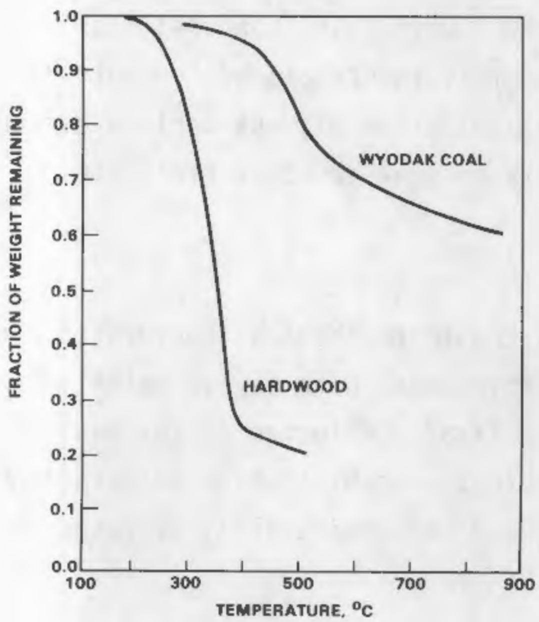

FIGURE 3. Biomass is More Volatile Than Coal[(f)]

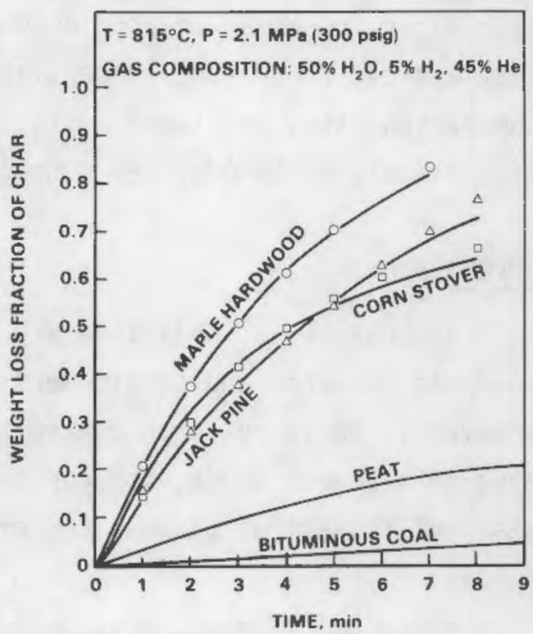

FIGURE 4. Biomass Chars Gasify Very Rapidly

- 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.

(f) Antal, M. J. 1978. Biomass Energy Enhancement. A report to the President's Council on Environmental Quality. Princeton University, Princeton, New Jersey.

- 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 establishing the potential of the process. Individual concepts are then combined into an integrated process. The integrated process is evaluated to verify process feasibility at a reasonable scale. This research approach is shown conceptually in Figure 5.

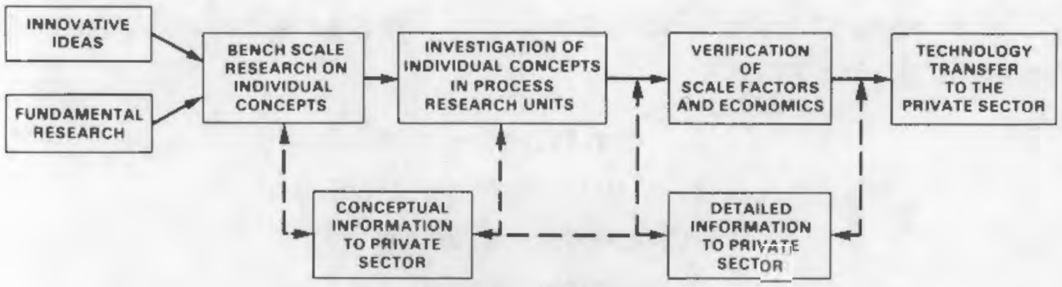

FIGURE 5. Program Approach

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 the government and private industry becomes more practical.

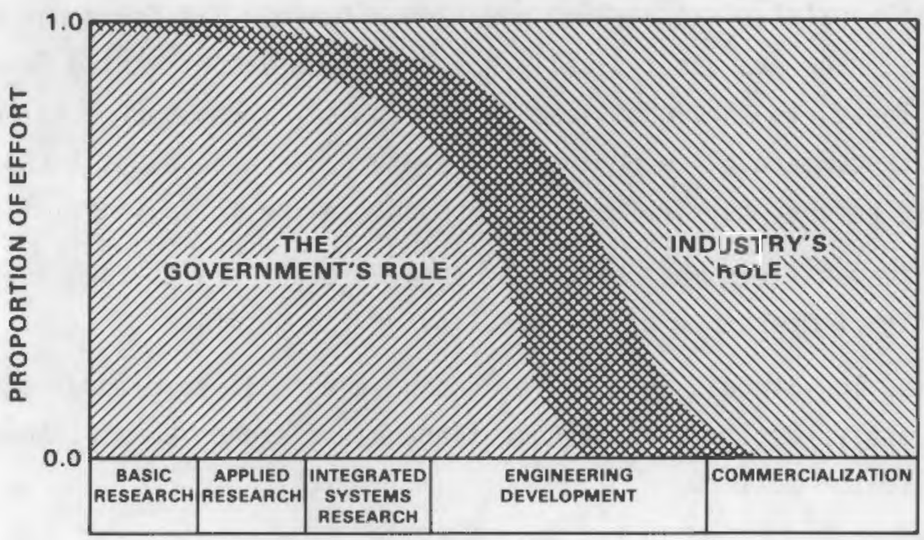

FIGURE 6. Industry Participation in the DOE Program

PROGRAM RESEARCH AREAS

The Biomass Thermochemical Conversion Program sponsored research in four major areas during FY85:

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, 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 provide heat for 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 be substituted 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 oil to fuel 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.

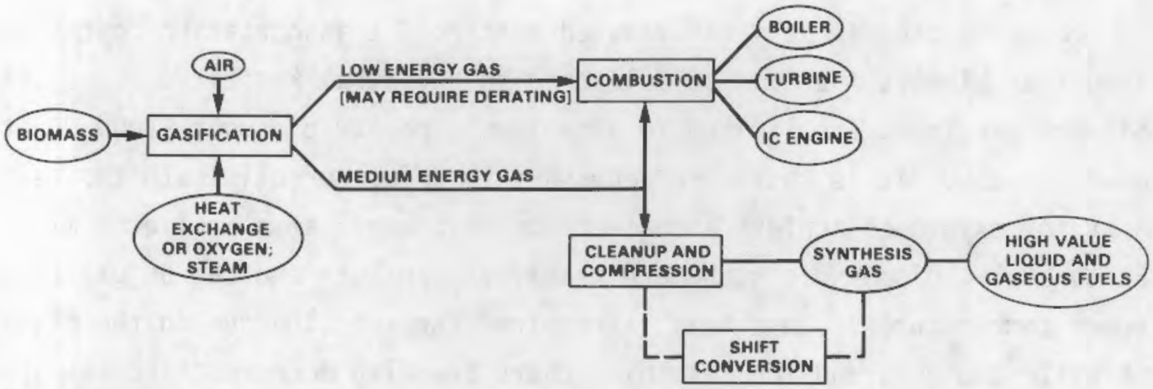

FIGURE 7. Thermochemical Gasification of Biomass

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 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.

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. It is therefore 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.

Over the past few years, the primary emphasis of gasification research sponsored by the Biomass Thermochemical Conversion Program has been to exploit the natural advantages of biomass to produce medium-Btu gas. The medium-Btu gas, depending on process concept, could be used 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.

1985 Gasification Program

The gasification projects sponsored by the Biomass Thermochemical Conversion Program in FY85 focused on two primary areas as shown in Figure 8.

First, four biomass gasifier process research units (PRU's) were operated to obtain data on gasifier designs for the production of medium-Btu fuel gas. Initial extended term tests ranging from three to five days of continuous operation were successfully completed by the Institute of Gas Technology, Battelle Columbus Laboratory, and University of Missouri-Rolla. The tests are important in developing process data such as accurate mass and energy balances, and they give crucial data on process reliability and other operation considerations. Based on results collected to date, comprehensive data packages on each of these three gasifiers were prepared at the request of DOE. The data packages represent a summary of the state-of-the-art for each of the PRU's. A comprehensive data package for a fourth gasification PRU operated by SynGas, Inc. under contract to Solar Energy Research Institute is expected in FY86.

In addition to the research with the PRU's, gasification studies were also conducted to resolve more basic research issues. This research included examination of the low temperature gasification of high moisture biomass feedstocks, studies of the role of catalysts in gasification processes, and studies of radiant heat transfer phenomena. The projects are shown in Figure 8 and are discussed in more detail below.

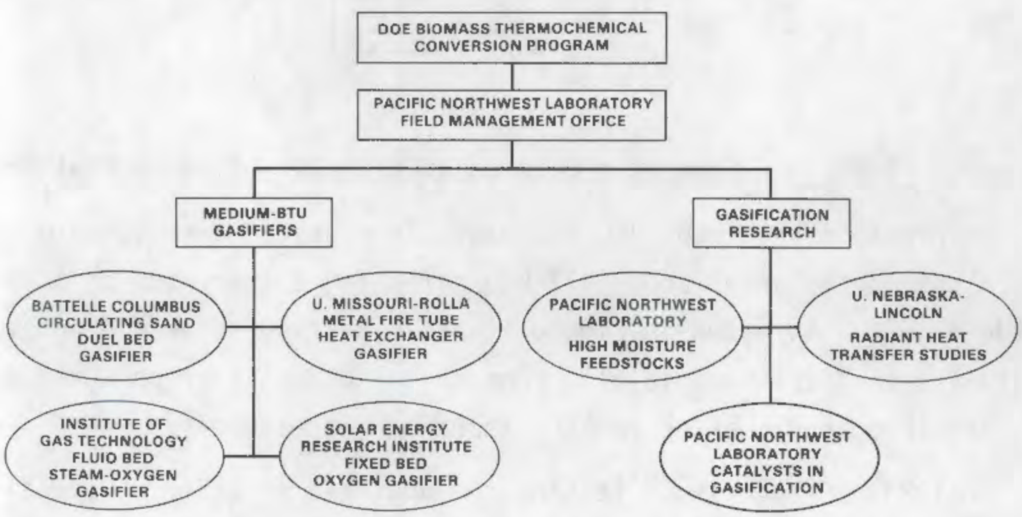

FIGURE 8. Gasification Research Projects

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, thus 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 separator. 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 photograph of the apparatus is shown in Figure 10.

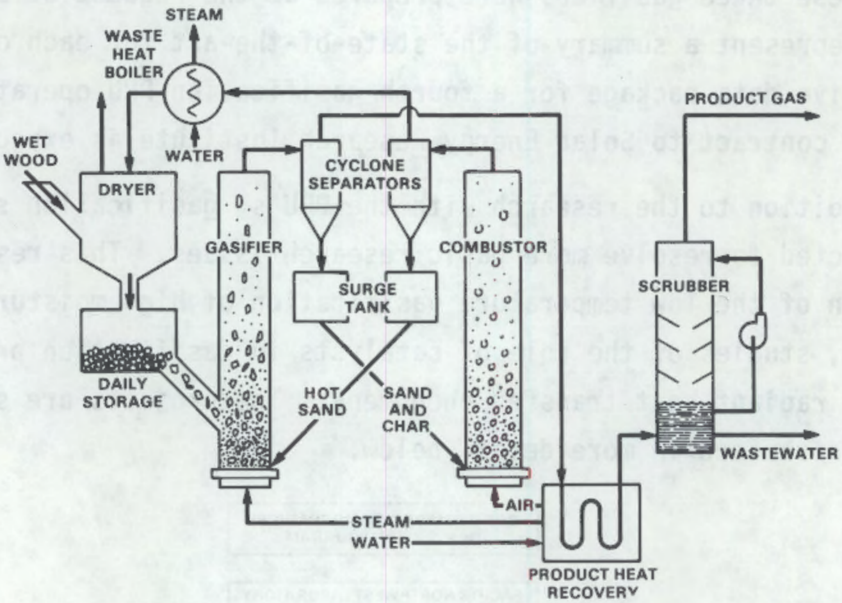

FIGURE 9. Schematic Diagram of Battelle-Columbus Gasifier

In previous research, BCL successfully produced a medium-Btu fuel gas with a heating value of about 475 Btu/scf using either wood chips or coarsely shredded bark. As shown in Figure 11, this heating value did not vary significantly for feedstocks containing from 8% to 40% moisture on a wet basis. Gasifier throughputs of up to 1800 $lb/hr/ft^2$ were achieved.

In 1985, BCL continued testing the dual bed gasifier. Operation of the PRU for extended periods up to 72 continuous hours has been achieved. Feedstocks ranging from chips to sawdust to hogged fuel have now been tested, and the performance of the gasifier is unaffected by these differences. Combustion tests during 1985 also showed that tars produced in the gasifier can be

FIGURE 10. View of Battelle-Columbus Gasifier

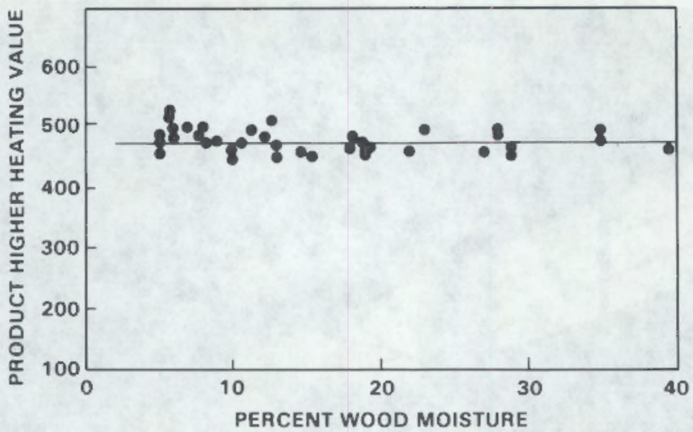

FIGURE 11. Heating Value of Product Gas is Independent of Feedstock Moisture Content

successfully burned in the combustor vessel. When gasifier tars were injected into the combustor, the resulting emissions were found to be well within environmental guidelines. Experimental conditions were similar to those which would be experienced in a commercial combustor. Based upon a request by DOE, BCL also compiled a comprehensive data package summarizing the progress to date for this gasifier.

THE UNIVERSITY OF MISSOURI, Rolla, Missouri, is investigating the technical feasibility of using an internal heat exchanger 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. This eliminates the need for pure oxygen in the gasifier. The university has constructed a 20-in. fluidized bed gasifier with an internal heat exchanger as shown in Figures 12 and 13. The configuration selected for actual testing uses thirty 1-in. diameter U-tubes spaced on a 2-in. pitch. The system has been operated at feed rates up to 400 lb/hr (10% moisture wood) and temperatures up to 1450°F.

During 1985, the University of Missouri completed experiments to determine the differences between feeding the gasifier from the top and the bottom of the fluidized bed. The top-fed configuration resulted in an overall thermal efficiency which was about 10% higher than the bottom-fed configura-

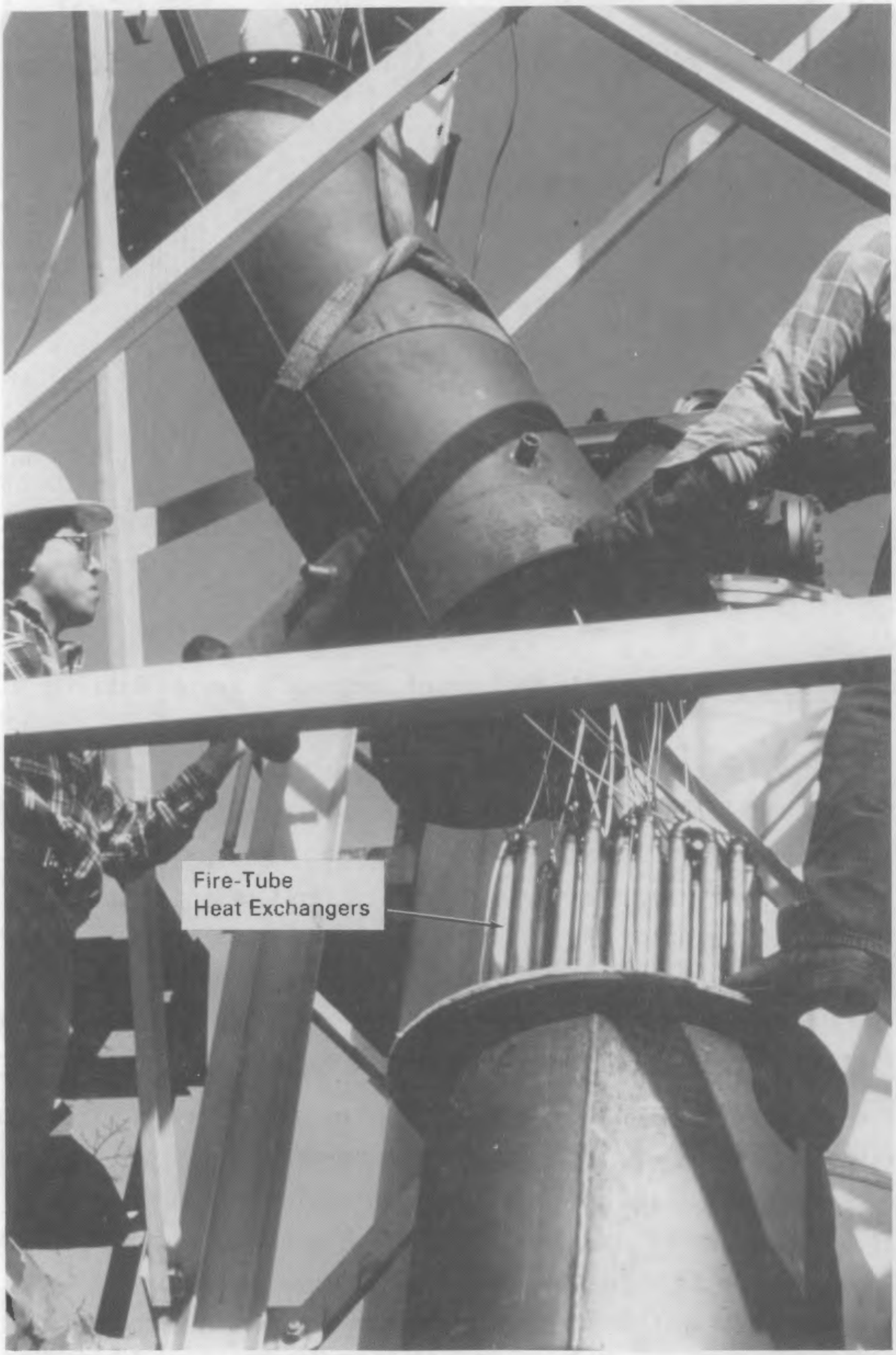

FIGURE 12. View of Gasifier at University of Missouri-Rolla

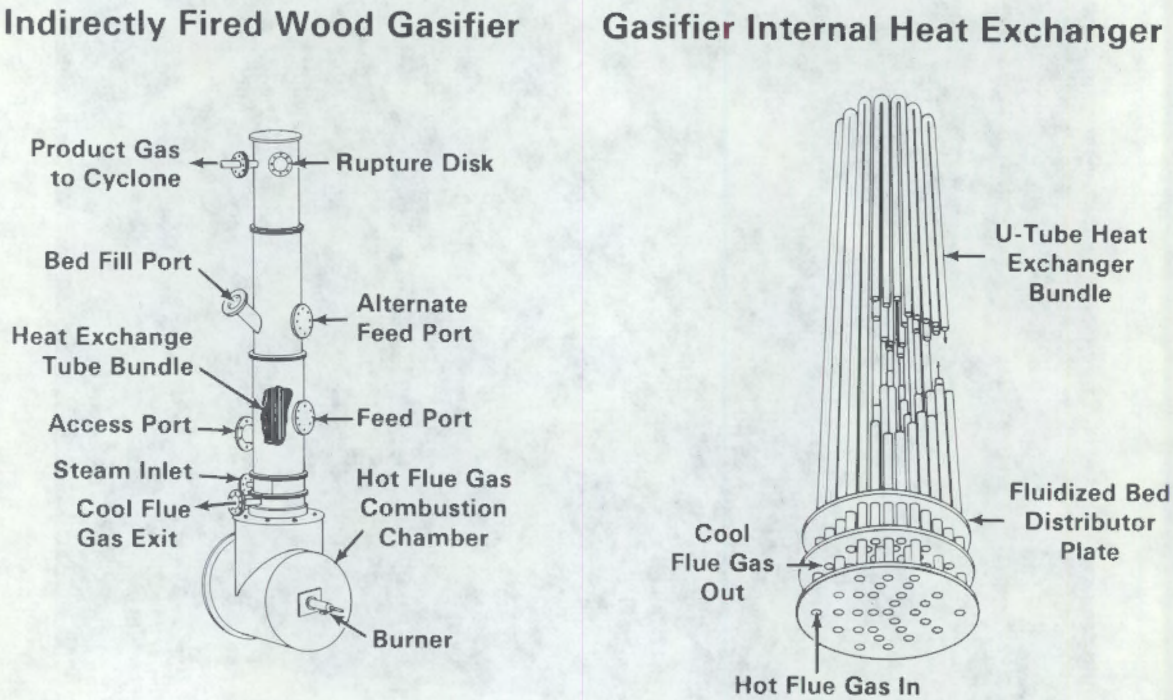

FIGURE 13. Schematic Diagram of Indirectly Heated Gasifier at University of Missouri-Rolla

tion. The top-fed configuration also yielded a product gas with higher energy content of about 525 Btu/scf as compared to about 475 Btu/scf when bottom-fed. Total tar production was also slightly lower for the top-fed configuration. The University of Missouri also completed its first extended term test. Continuous, uninterrupted operation of the gasifier was achieved for a period of five days. This test yielded valuable information on material and energy balances and helped confirm the operational feasibility of this concept. The university also compiled a comprehensive data package at the request of DOE.

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 capable of operation at pressures up to 500 psia has been constructed and is shown conceptually in Figure 14. Wood is fed from a pressurized lockhopper to a pressurized, live-bottom feed hopper and is metered into the gasifier unit. In previous research, wood feedstock throughputs of about 1000 $lb/hr/ft^2$ 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.

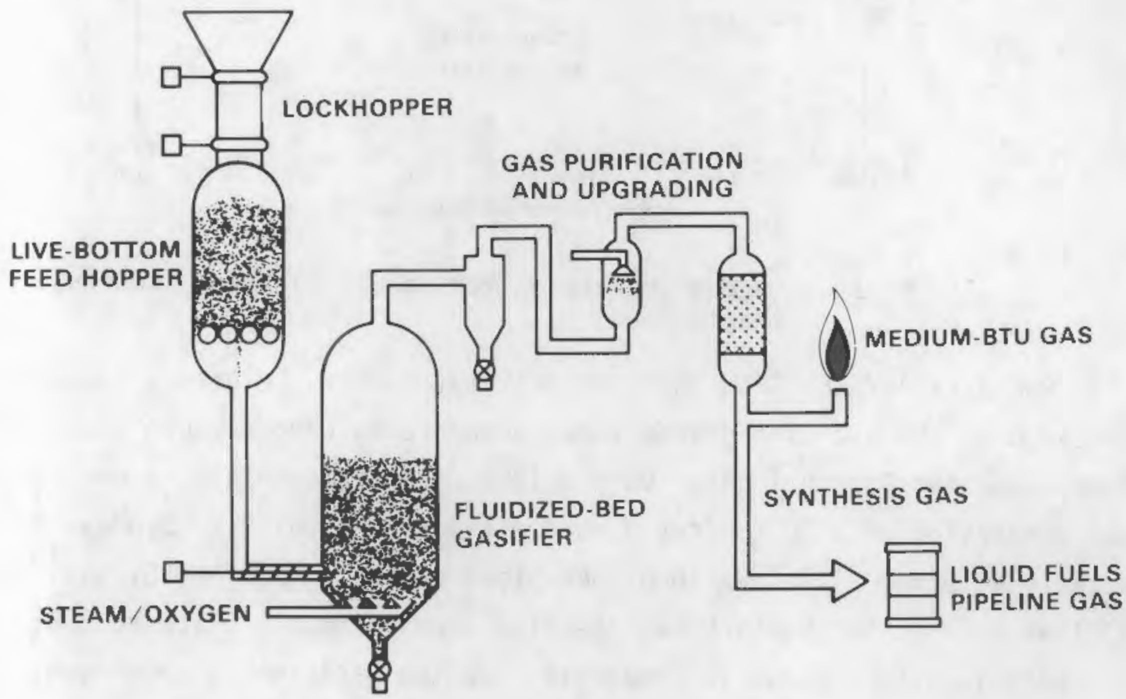

FIGURE 14. Schematic Diagram of Gasifier at Institute of Gas Technology

During 1985, IGT conducted an extensive matrix of tests to determine the effect of various experimental parameters such as pressure, temperature, and feed rates on product yields. The tests were conducted over the range 1390 to 1800°F, 100 to 30D psig, and feed rates up to 1030 lb/hr. The effect of the temperature of the fluidized bed on the carbon conversion is shown in Figure 15. IGT also completed continuous, extended-term tests of up to three days in length. The tests confirm the mass and energy balances of previous shorter term runs and also confirm the ability of the facility to operate at pressure for extended periods. Based on these results, IGT prepared a comprehensive data package for DOE which summarizes research progress to date.

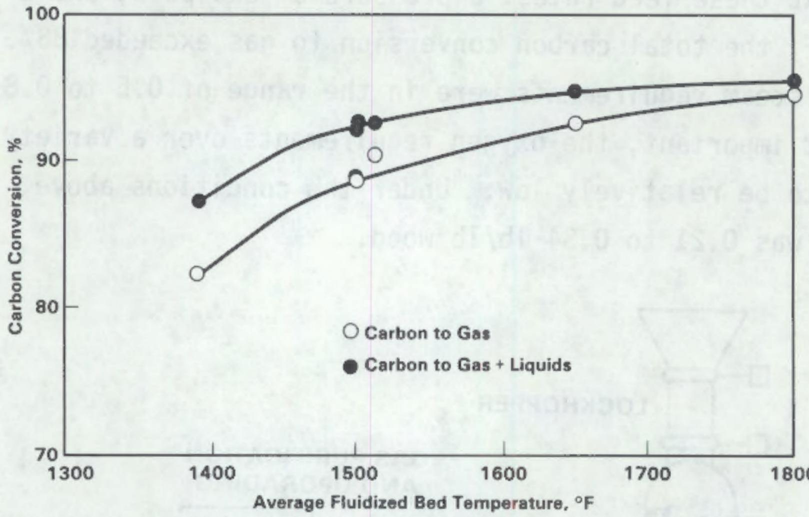

FIGURE 15. Carbon Conversion Versus Gasification Temperature (Maple Feed)

SOLAR ENERGY RESEARCH INSTITUTE (SERI), Golden, Colorado, is conducting research on the use of a pressurized, down-draft, oxygen-blown gasifier to produce medium-Btu fuel gas. During 1985, the research effort has centered on the conversion of a 20 ton/day down-draft gasifier built by SynGas, Incorporated (SGI) from air-blown to oxygen-blown capability. The SGI gasifier is similar to a SERI PRU which was operated experimentally prior to 1985. A view of the SGI unit is shown in Figure 16, and the gasifier is shown schematically in Figure 17. The conversion of the gasifier was completed at the end of FY85, and testing to determine mass and energy balances, oxygen consumption and other experimental parameters will be conducted in early FY86. SynGas, Inc. will prepare a comprehensive data package based on the results obtained with their gasifier.

During 1985, SERI conducted research to provide backup information for the gasifier scale-up. A 0.05 ton/day transparent laboratory gasifier was converted to oxygen operation to provide a test bed for measuring temperature and gas composition in the reactor. A small inverted downdraft gasifier was also coupled to a molecular-beam mass spectrometer to provide the first in-situ spectra of an operating gasifier. In a seven-minute run it was possible to clearly distinguish initial oxygen breakthrough during start-up,

FIGURE 16 Photograph of SGI Gasifier

primary oil formation during most of the operation, and finally char-only gasification when the wood fuel was exhausted. This small gasifier was also run in the updraft mode, producing large quantities of primary oil.

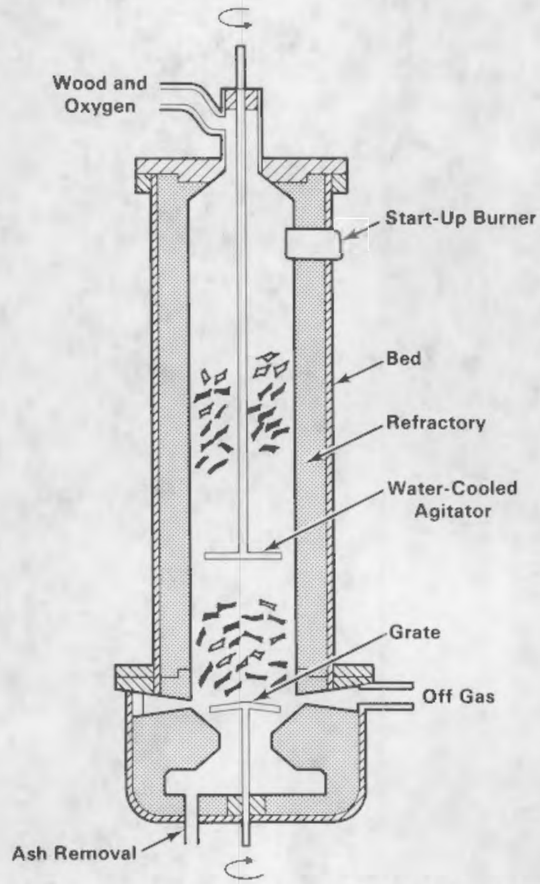

FIGURE 17. Conceptual Diagram of SGI Down-Draft Gasifier

Medium-Btu Gasification Research

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

During 1985, initial reaction parameter studies were conducted in a small laboratory-scale batch reactor at PNL. The experiments studied the effect of feedstock, temperature and catalyst loading on the product gas. As shown in Figure 18, the conversion conversion was highest at about 450°C in the presence of an nickel/alkali catalyst. Under these conditions, the heating value of the product gas typically ranged from 350 to 425 Btu/scf. It is interesting to note that the product gas is composed almost entirely of methane (~ 40%), hydrogen (~ 8%), and carbon dioxide (~ 52%) and could therefore potentially be upgraded to a high-Btu gas by simply removing CO_2.

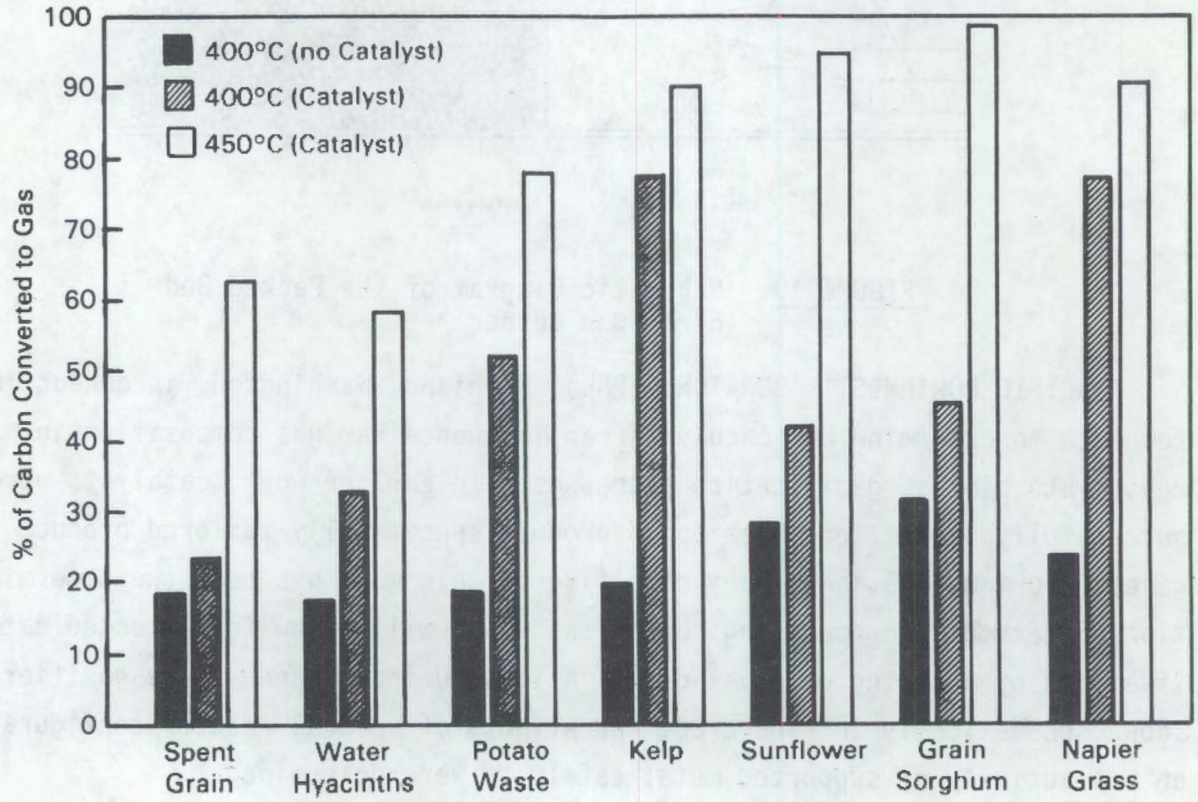

FIGURE 18. Carbon Conversion to Gas

UNIVERSITY OF NEBRASKA, Lincoln, Nebraska, has been investigating the radiant heat transfer capabilities of indirectly heated fluidized bed gasifiers. The research has concentrated on evaluating the use of indirectly heating a gasifier with infa-red emitting fire-tubes internal to the reactor. Radiant heating provides the potential advantage of high heat transfer rates. During 1985, the university successfully determined configurations for ceramic fire-tubes which would allow steady operation without failure from thermal shock. Burner tubes were operated for more than 60 hours with repeated thermal heating/cooling cycles. A schematic diagram of the sample fire-tube is shown in Figure 19. The University of Nebraska also completed extensive modeling studies on radiant energy transfer. Based on the results to date, a conceptual reactor design was developed.

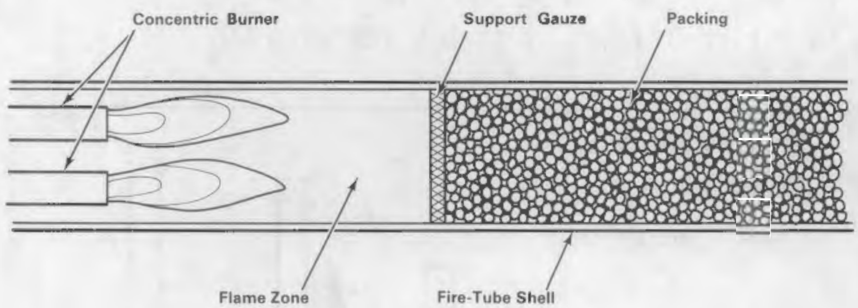

FIGURE 19. Schematic Diagram of the Packed Bed Fire-Tube Burner

PACIFIC NORTHWEST LABORATORY (PNL), Richland, Washington, is conducting research to determine how catalysts can influence raw gas composition in medium-Btu biomass gasification processes. In earlier work, catalysts were successfully identified which could produce specifically tailored product gases. During 1985, a primary objective of this work has been the determination of methods and operating conditions which will allow for extended catalyst lifetimes by avoiding catalyst deactivation. Using a bench-scale gasifier shown schematically in Figure 20, the effects of several reactor configurations on the activity of supported metal catalysts were determined.

The tests indicated that activities of several catalysts could be maintained for long periods by containing the catalysts in a second fluidized bed vessel immediately downstream from the actual gasifier. This configuration separates the catalyst from primary tar-forming reactions in the gasifier and provides rapid heat transfer to the catalyst surface, reducing "cold spots" and coke formation. In addition research indicated that nickel catalysts in the second fluidized-bed vessel were highly effective in destroying condensible organic products while increasing product gas yields. The condensible organics are potentially major wastewater and environmental contaminants. These results

The research sponsored by the Biomass Thermochemical Conversion Program focuses on biomass direct liquefaction processes capable of producing true hydrocarbon fuels. Biomass direct liquefaction processes are those which yield liquids as primary initial products, usually at moderate temperatures (250 to 600°C). Pyrolytic and catalytic liquefaction processes which produce biocrude oils are examples. The crude oils produced in these processes are chemically different than petroleum hydrocarbon oils but can be upgraded into true hydrocarbon products. The ability to generate true hydrocarbon fuels is very important to ensure compatibility with existing gasoline based fuels and fuel distribution systems. Thermochemical conversion processes are the only ones capable of producing true hydrocarbons from biomass.

Projects being funded by the Biomass Thermochemical Conversion Program are shown in Figure 21. The research is directed at exploring methods for generating biocrude intermediates and then upgrading them into high value hydrocarbon fuels.

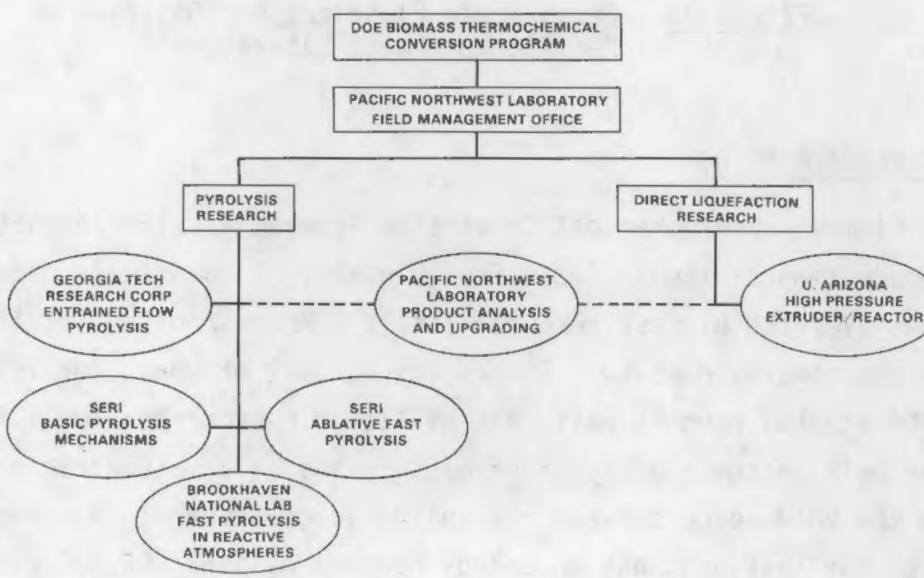

FIGURE 21. Liquid Fuels Projects Sponsored By The Thermochemical Conversion Program

Pyrolytic Liquefaction Research

Pyrolysis refers to the heating of biomass in the absence of air. Traditionally, pyrolysis has been used to produce charcoal. Conventional indicate that the catalysts can potentially be used for gas clean-up applications as well as tailoring the primary gas product.

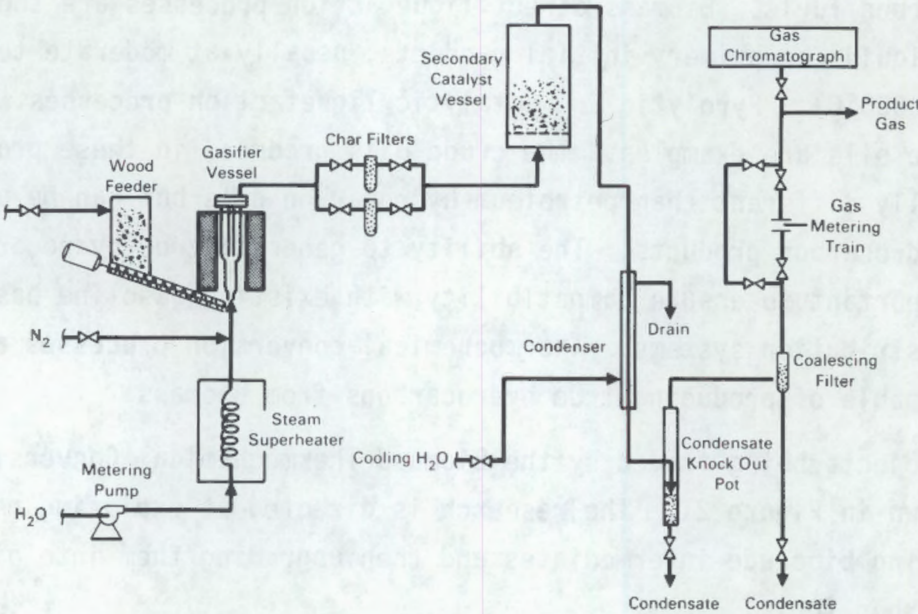

FIGURE 20. Bench-Scale Fluidized Bed Gasifier at Pacific Northwest Laboratory

LIQUID FUELS TECHNOLOGY

The Biomass Thermochemical Conversion Program is also conducting research on the production of liquid fuels from biomass. Liquid fuels offer several advantages over the biomass resource itself. Most importantly, liquid fuels have a higher energy density. The energy content of wood, for instance, is about 8500 Btu/lb, roughly half that of liquid hydrocarbon fuels. The effective bulk energy density of biomass solids on a volumetric basis is even lower if the void space between the solids is considered. A cubic foot of dry wood chips for instance, has an energy content of about 90,000 Btu. This is less than one tenth the energy density of gasoline which contains about 928,000 Btu/ft^3. The higher energy density of liquid fuels from biomass allows the products to be transported more economically and to be more easily stored. Liquid fuels also match existing end-use patterns, particularly in the transportation sector.

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, 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. By carefully controlling both the heating rate and the temperature, the yields of liquid biocrude products can be increased to over 65% by weight on a moisture, ash-free basis. Under some conditions, up to about 20% high value olefinic and BTX products can be produced.

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

- using fast pyrolysis to produce high yields of low-cost biocrude oil substitutes.
- investigating 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

Four research projects are currently being conducted in fast pyrolysis.

GEORGIA TECH RESEARCH CORPORATION, Atlanta, Georgia, is conducting research on rapid pyrolysis of biomass with the goal of producing low cost liquid products. 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 Figures 22 and 23, consists of an entrained, upflow reactor and an oil recovery system that allows partial on-stream fractionation of the product. In previous research Georgia Tech Research Corporation performed experiments 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%.

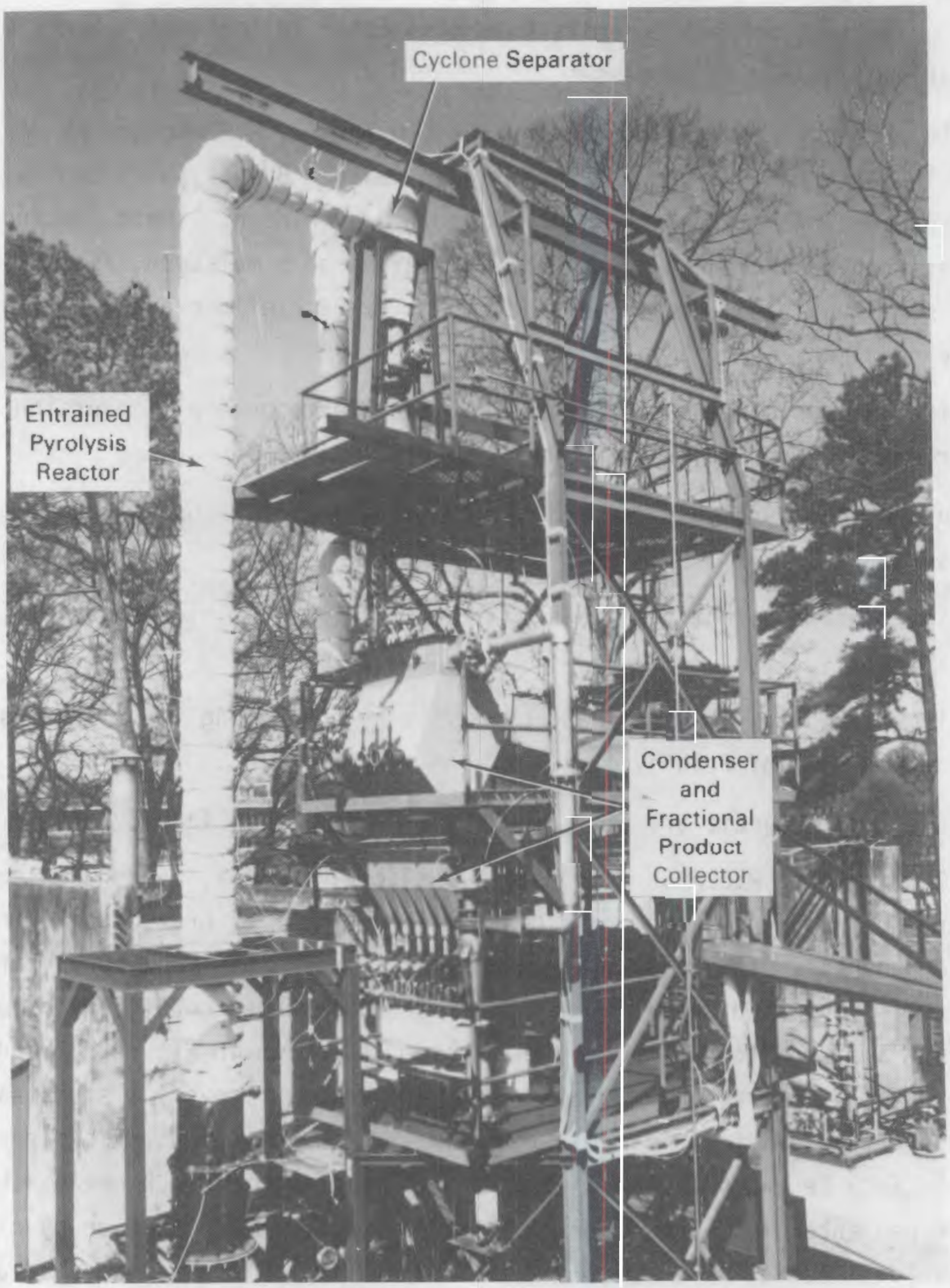

FIGURE 22. View of Georgia Tech Research Corporation Pyrolysis Reactor

During 1985, modifications to reduce the diameter of the pyrolyzer from 8-in. to 6-in. were completed and the modified unit was successfully operated. The modifications allow the wood residence times to be reduced to as little as half of that in the previous configuration. Fourteen experimental test runs were made. The test runs resulted in better mass and energy balances for the pyrolyzer. Additional testing in 1986 should complete parameter optimization studies.

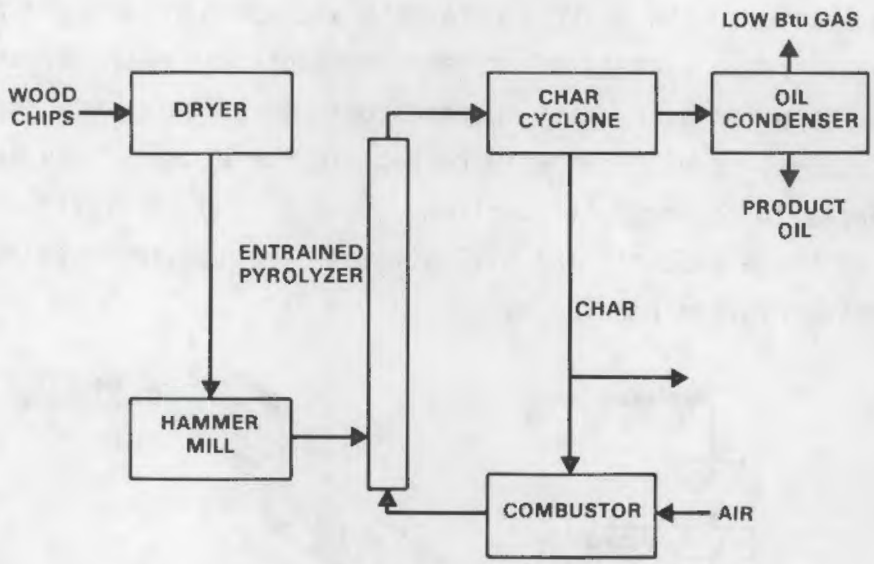

FIGURE 23. Schematic Diagram of Entrained-Flow Pyrolysis Reactor at Georgia Tech Research Corporation

SOLAR ENERGY RESEARCH INSTITUTE (SERI), Golden, Colorado, is conducting two projects on the fast pyrolysis of biomass. The first 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 methods for upgrading the reaction products. 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 subsequently vaporizes. Heat-up rates as high as 500,000°C/sec can be obtained at the sample surface. A schematic of the reactor system is shown in Figure 24. The initial products formed in the reactor section are primary pyrolysis vapors which can be condensed as pyrolysis oils at yields of about 60%.

During 1985, SERI completed a sophisticated computer model which simulates the behavior of biomass under the pyrolysis conditions in the ablative reactor. The computer model closely predicts behavior in the experimental reactor system and provides a useful tool for examining various reaction conditions. SERI also initiated studies on a potential method for upgrading the pyrolysis vapors. The primary biomass pyrolysis tars in the vapor phase would be passed over zeolite catalysts downstream from the pyrolysis reactor. The zeolite catalysts are known to produce gasoline-like hydrocarbons from a variety of oxygenated feedstocks such as methanol. Preliminary studies using mass spectroscopic techniques show that at least one zeolite catalyst is reactive with respect to the biomass tars and will produce major changes in the product spectrum. Work during 1986 will confirm the identity of these products and will attempt to optimize reaction conditions for producing hydrocarbon fuels.

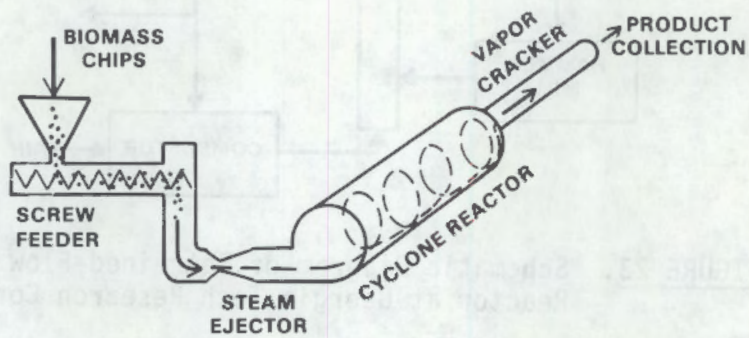

FIGURE 24. Ablative Biomass Pyrolysis Reactor at Solar Energy Research Institute

The second project as SERI is examining the basic reaction mechanisms occurring during biomass fast pyrolysis. 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 moderate temperatures (400 to 550°C). Representative competing pyrolysis reaction pathways are shown in Figure 25.

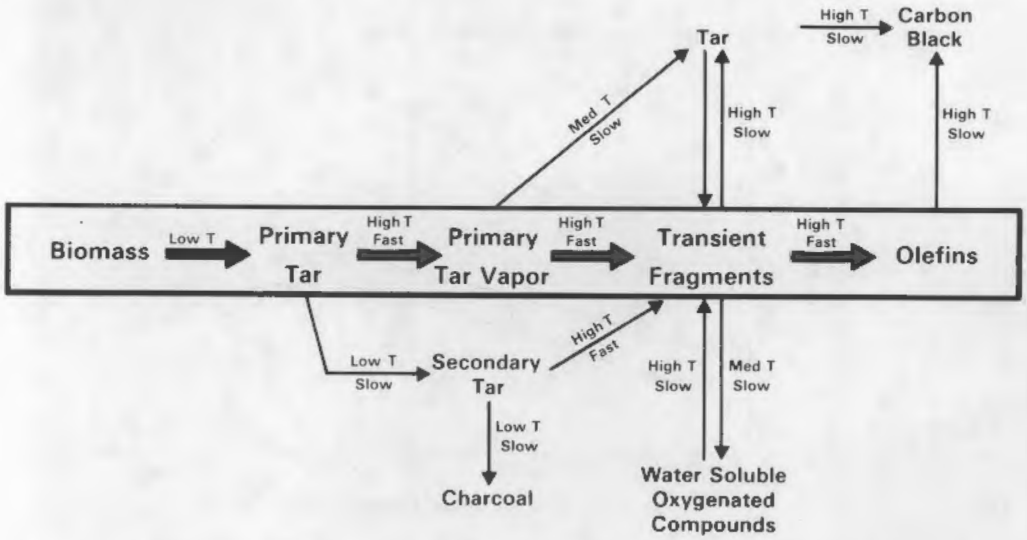

FIGURE 25. Reactive Pathways for Biomass Pyrolysis

During 1985, SERI completed a comprehensive study of the primary and secondary pyrolysis cracking mechanisms. Primary tars are formed above a temperature threshold of about 370 to 400°C but are relatively insensitive to temperatures up to about 500°C at short residence times. The primary vapors begin cracking at 500°C and are completely cracked at a temperature of 900°C, even at short residence times of a few hundred milliseconds. These studies help provide a better understanding of the pyrolysis process itself and should aid in the development of upgrading processes as well.

BROOKHAVEN NATIONAL LABORATORY, Upton, New York, is investigating the effect of conducting rapid pyrolysis in the presence of reactive atmospheres. The research has shown that the yields of pyrolysis products can be significantly altered when the reaction is conducted in the presence of methane. Using a bench-scale, entrained downflow reactor, biomass is pyrolyzed at temperatures of 800 to 1100°C in methane at pressures of 50 to 500 psi. With methane present, the yields of high-value products such as ethylene, benzene, toluene, and xylene can be up to about 2.5 times greater than those where an inert gas such as helium is used. The presence of the methane can, therefore, lead to significantly upgraded products at relatively moderate pyrolysis heat-up rates.

Research in 1985 quantified the effect of methane on the biomass pyrolysis reactions and contributed to understanding the reaction mechanisms. As shown in Figure 26, the maximum ethylene, BTX, and total hydrocarbon yields from

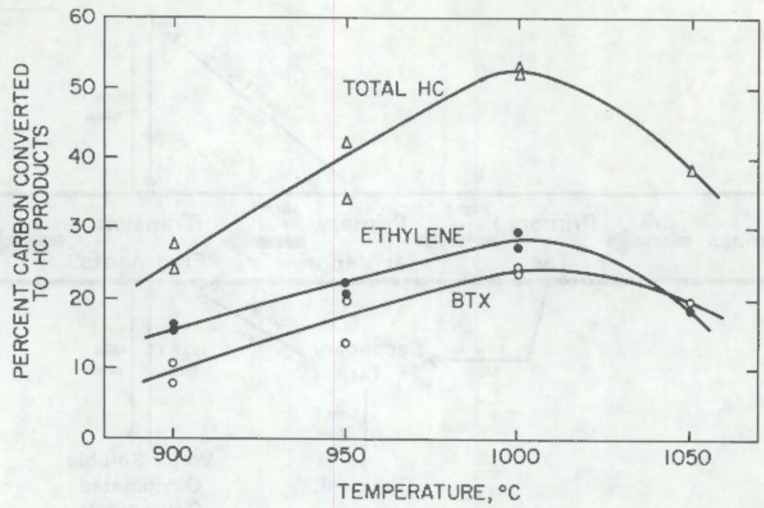

FIGURE 26. Pyrolysis of Wood in a Methane Atmosphere

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 doubles. Experiments have suggested that the effect may arise from the formation of free radicals from the biomass decomposition which subsequently react with methane. Further exploration of these reaction mechanisms is continuing.

Catalytic Liquefaction Research

Catalytic direct liquefaction research, at this time, is based on a concept first proposed by the Pittsburgh Energy Research Center. 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°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.

In 1980 and 1981, this process and an aqueous slurry version, proposed by Lawrence Berkeley Laboratory, were tested in a DOE research facility located at Albany, Oregon. This research showed the technical feasibility of producing biomass derived liquids by both the oil slurry and aqueous slurry process variations. In one test run during 1981, over 11,000 lbs of direct liquefaction oils were produced during operation in the oil slurry mode.

Despite technical progress, the results indicated that the processes were not economically competitive at that time, due in part to the large oil recycle requirement. As a result, the Albany facility was deactivated in 1981. The Thermochemical Conversion Program is attempting to improve the competitiveness of direct liquefaction through the use of increased feedstock slurry concentrations.

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. The University of Arizona has designed and constructed an integrated extruder/static mixer liquefaction system as shown in Figure 27. The static mixer is expected to allow adequate mixing and agitation of the viscous slurries.

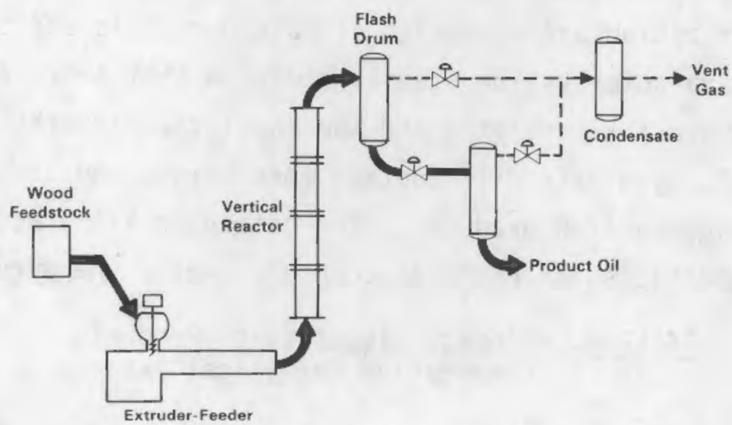

FIGURE 27. Schematic Diagram of Catalytic Liquefaction Unit at University of Arizona

In 1985, the University of Arizona completed the construction of the research unit and began experimental shakedown operation. Initial tests using wood feedstocks and a petroleum based asphalt slurry medium confirmed the operational feasibility of the unit during shakedown. Based on these tests, the unit was then operated using wood in a wood-oil slurry. The initial wood-oil test was completed at the end of FY85 and was highly successful.

This test run operated at about 3000 psi and 370°C for a period of 3.5 hours. The crude produced was low in oxygen content and had a high heating value. Properties of the oil are summarized in Table 1. Additional testing is expected in 1986.

TABLE 1. Properties of Crude Oil from Wood Produced by the University of Arizona (Dry Basis)

Elemental Analysis:	
C	83.4%
H	7.9%
O	8.5%
Heating Value (HHV)	16,000 Btu/lb

Product Characterization and Upgrading Research

In addition to research on liquefaction concepts, the Thermochemical Conversion Program is also sponsoring research on the characterization of the biocrude products and their subsequent upgrading into gasoline-compatible hydrocarbon fuels. This research is described below.

PACIFIC NORTHWEST LABORATORY, Richland, Washington, is conducting research on the characterization and upgrading of both pyrolytic and catalytic liquefaction oils. Characterization studies indicate that there are significant differences between the pyrolytic and the catalytic liquefaction oils. As shown in Table 2, pyrolysis oils contain more oxygen and are less viscous than the catalytic liquefaction products. The catalytic liquefaction products contain large quantities of phenolic compounds while the pyrolysis oils have

TABLE 2. Biomass Liquefaction Products Comparative Analytical Data

Elemental Analysis (MAF)	Catalytic 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	1.5%	1.4%
Moisture and Heating Value		
% H_2O	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

large concentrations of organic acids. These differences directly impact the methods for upgrading these products.

During 1985, research at PNL has concentrated on upgrading the biocrude liquids to gasoline-like motor fuels. This research uses nickel/molybdenum and cobalt/modybdenum catalysts in a continuously fed, bench-scale reactor to hydrotreat the liquefaction crude oils. Initial research has focused on the catalytic liquefaction oils due to their lower initial oxygen content and higher stability. Hydrotreating under conditions of 350 to 400°C at pressures of 2000 psi yields primarily hydrocarbon materials. Comparisons of key constituents and of relative properties of the crude and upgraded products are shown in Tables 3 and 4.

TABLE 3. Comparison of Typical Constituents of Biomass Catalytic Liquefaction Biocrude Oil and Hydrotreated Product (Albany TR-7 Oil)

Biomass Crude Product	Refined Biomass Oil
Cyclic Keytones	Cyclohexane
Unsaturated Cyclic Keytones	Alkyl-Cyclohexanes (to C-10)
Alkyl-Phenols	Benzene
Methoxy-Phenols	Toluene
Di-Phenols	Xylene
Napthols	Other Alkyl-Benzenes

TABLE 4. Comparison of Properties of Biocrude Oils and Hydrotreated Product (Albany TR-7 Oil)

	Biocrude Oil	Refined Biomass Oil
Hydrogen to Carbon Ratio	1.21	1.61
Oxygen Content (%, MAF Basis)	11	0.3
Density (g/cm^3)	1.19	0.83
Viscosity (cPs @35°C)	100,000	1.1
Heating Value (HHV, MAF Basis)	15,800	18,900

Pacific Northwest Laboratory also initiated research on the upgrading of the pyrolytic liquefaction oils. The pyrolytic oils are expected to be less expensive to produce but more difficult to upgrade due to their higher oxygen content and lower stability. The lower stability of the oil results in extensive char formation and reactor plugging when the pyrolysis oils are hydrotreated under conditions similar to the catalytic liquefaction products. Preliminary research has indicated that a two-step process may be feasible for upgrading the pyrolysis oils. The initial step would use a mild treatment with a nickel catalyst at relatively low temperature (260 to 280°C) followed by a second hydrotreating step similar to that used with the catalytic liquefaction products. Additional research on this concept will be conducted in FY86.

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 examined unique, innovative combustion systems or special issues involved in burning biomass fuels.

The Biomass Thermochemical Conversion Program is currently sponsoring direct combustion research to determine the technical feasibility of converting the heat released from 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 28, the Program sponsored two biomass direct combustion projects during 1985.

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 a gas turbine can be practically fueled with solid biomass fuels such as wood. In the Aerospace system,

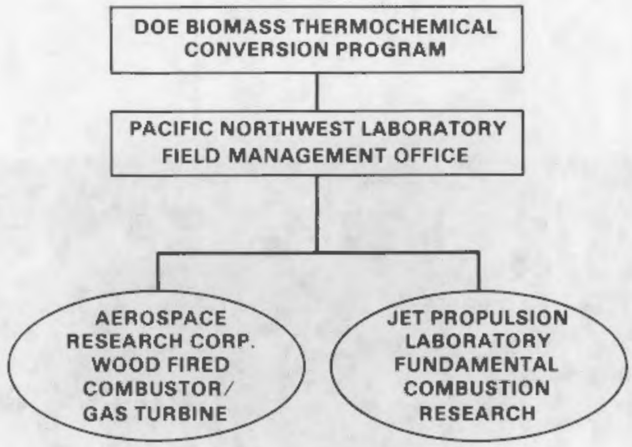

FIGURE 28. Direct Combustion Research Projects

the integral jet engine combustor is replaced with an external combustor utilizing wood as fuel. Hot combustion gases from a pressurized wood-fired suspension burner pass through a series of cyclones to remove particulate matter and are injected directly into the gas turbine. A schematic diagram of this concept is shown in Figure 29. In previous trials using a 375-kW combustor/ gas turbine, over 500 hours of operation were completed with no significant signs of erosion or corrosion to the turbine blades. Tests showed that particulate loading in the 375-kW system was very low.

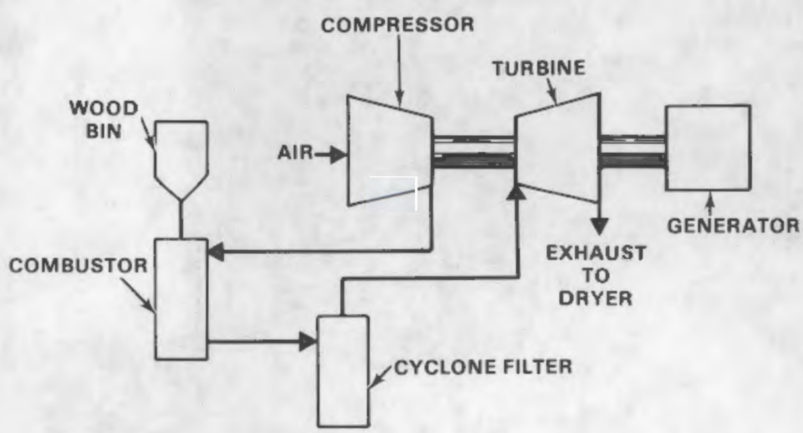

FIGURE 29. Schematic Diagram of Combustor/Gas Turbine at Aerospace Research Corporation

During 1985, Aerospace Research Corporation completed construction of a 3-MW combustor/gas turbine and electrical generator unit similar in design to the earlier system. The 3-MW unit is shown in Figures 30 and 31. The large

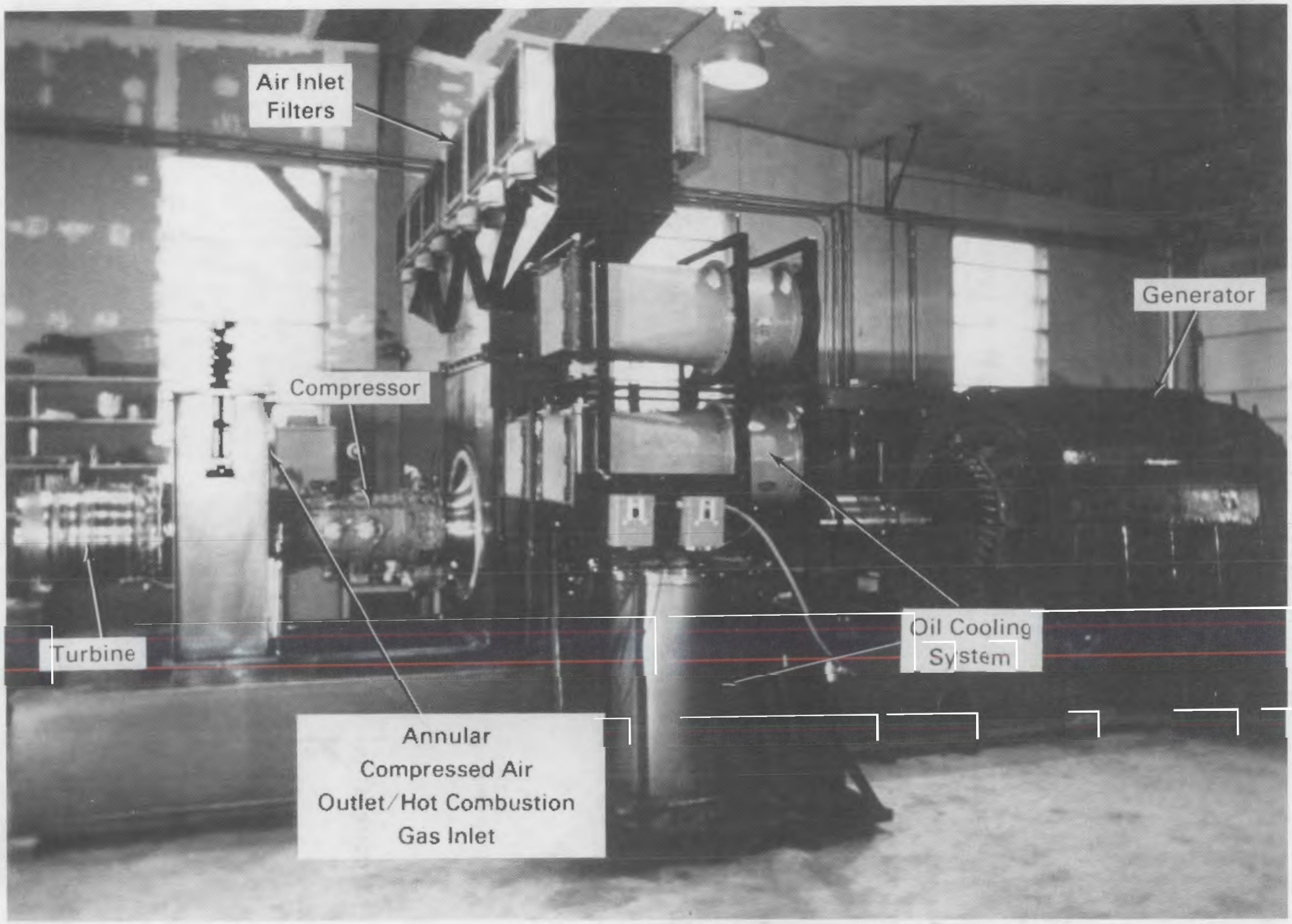

FIGURE 30. View of Gas Turbine and Generator System

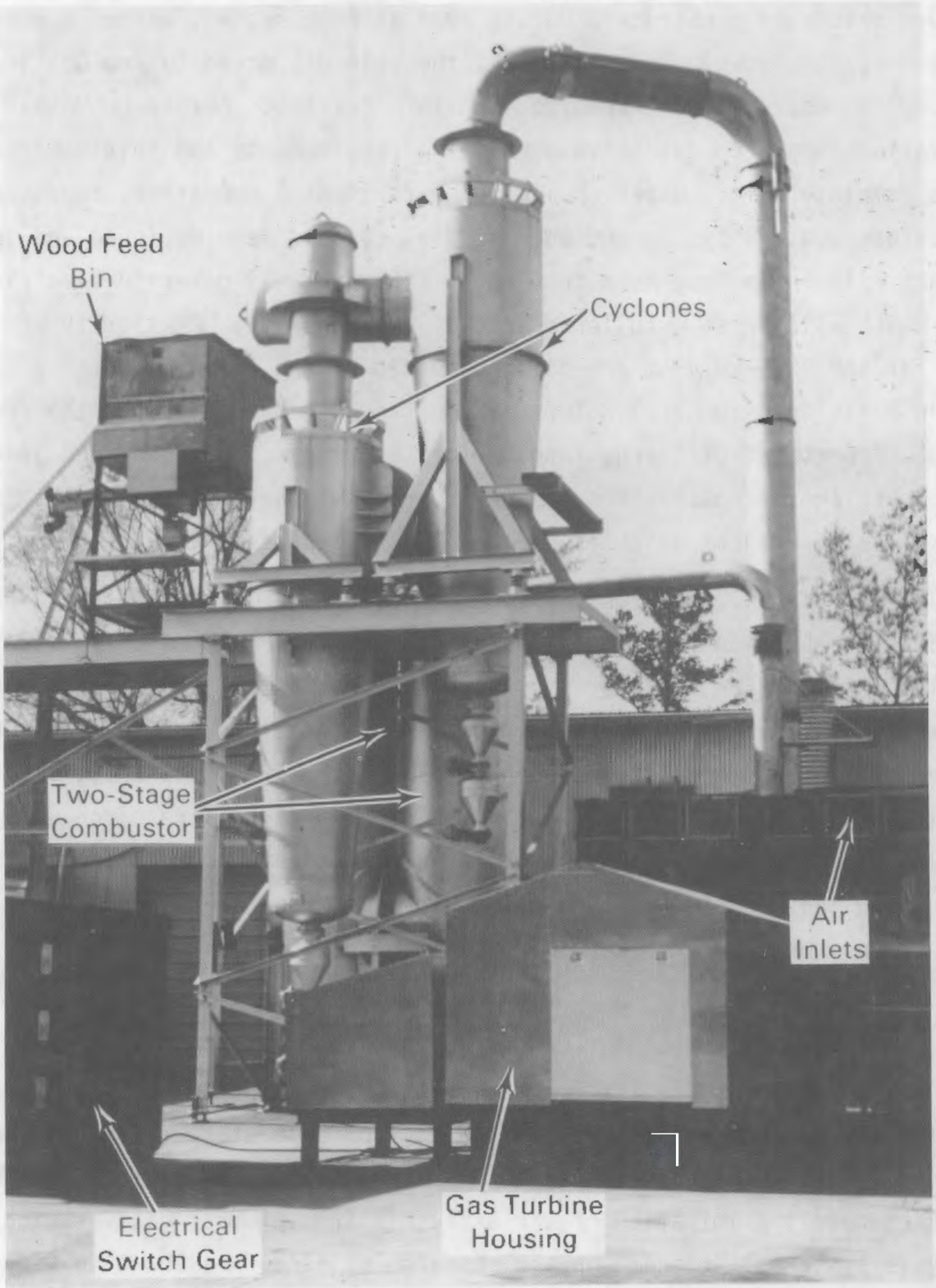

FIGURE 31. View of 3-MW Combustor/Gas Turbine System

unit was initially constructed during 1984 at Roanoke, VA, where it underwent preliminary shakedown. In early FY85, the unit was moved to Red Boiling Springs, TN, where it will undergo long-term testing. Aerospace Research Corporation completed extensive permitting requirements and initiated shakedown of the complete unit. Based on initial experimental operation, improved temperature control system and wood feeding systems were designed and installed. The unit will begin long-term testing in FY86 and will generate electrical power which will be sold to Tennessee Valley Authority. A majority of the funds for the 3000-kW unit are being provided by the private sector. The Allison Division of General Motors is donating a gas turbine for the project. In 1985, 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 developed a predictive model that correlates combustion behavior with wood particle size, type, moisture content, and heating value. Experimental verification of the predictive model was also performed. In addition, the research explored the effect of additives such as alkali salts on combustion behavior. The results of this research will be used to develop a more complete understanding of fundamental combustion reactions. By applying this knowledge, combustion processes that are both more efficient and more environmentally acceptable should be possible.

PROGRAM SUPPORT ACTIVITIES

During FY85, 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, and a examination of tar effluents from biomass gasification and pyrolysis systems. Program support research projects are shown in Figure 32.

SCIENCE APPLICATIONS INTERNATIONAL CORPORATION (SAIC), Arlington, Virginia, conducted engineering and economic studies to assess advanced biomass conversion concepts. During 1985, SAIC completed analyses on two advanced biomass conversion technologies. These include an entrained-flow

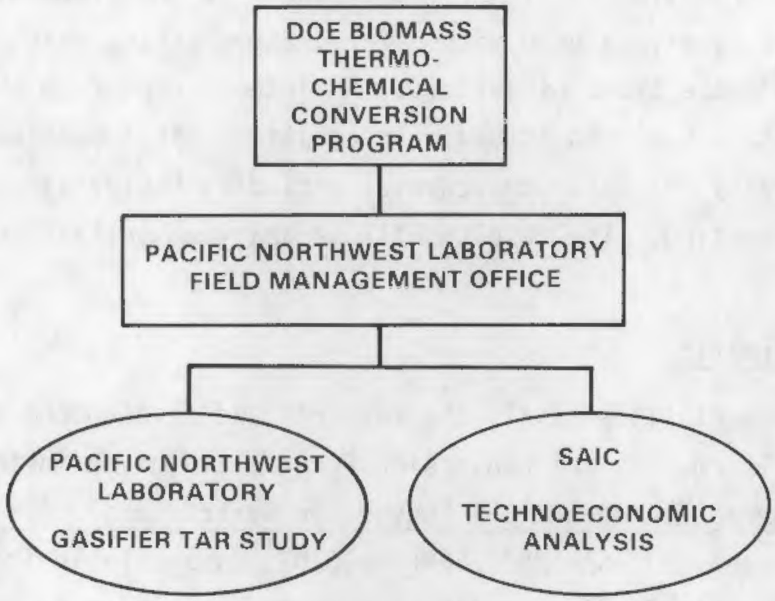

FIGURE 32. Program Support Research Projects

pyrolysis system for production of fuel oil based on work at Georgia Tech Research Corporation and a wood-fired gas turbine system with steam injection for production of electricity based on work at Aerospace Research Corporation. For an entrained-flow pyrolysis system, assuming feedstock costs of $25/dry ton, the resulting fuel product ranged in cost from $4.33/MM Btu (1000 TPD capacity) to $6.DO MM Btu (20D TPD). Analysis of the wood-fired gas turbine system suggested that a injection of steam into the hot combustion gases would offer advantages over the same system where steam is not injected. Power output would increase significantly with the steam injection, resulting in a reduction of levelized power costs. These costs range from 22 to 35 mills/kWh for the direct fired system with steam injection as compared to 33 to 52 mills/kWh for the system without steam injection.

PACIFIC NORTHWEST LABORATORY (PNL), Richland, Washington, completed an extensive analysis of condensates from selected pyrolysis and gasification units. Comprehensive analysis of tars and condensates which had been produced in various research units was made. Analysis included ash content, heating value, elemental analysis, density, chemical constituent identification, and other tests. The results show a continuous transition from highly oxygenated pyrolyzates formed at low temperatures to phenols at medium temperatures to refractory poly-aromatics at higher temperatures in the systems. Analysis of the tars appears to give a good method for cross-checking reaction temperature measurements in these types of systems. An interim report on the characterization of the tars has been issued. In addition, PNL completed studies of the biological activity of these condensates including bacterial assays and mammalian skin testing. The results will be analyzed in 1986 and a report will be issued.

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 1985 Biomass Thermochemical Conversion Contractors' Meeting, October 1985. This document, PNL-SA-13571/CONF-851D167, 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.

GASIFICATION

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

Feldmann, H. F., M. A. Paisley, and H. R. Appelbaum. "Conversion of Forest Residues to a Methane-Rich Gas in a High Throughput Gasifier." In Proceedings of the 1985 Biomass Thermochemical Conversion Contractors' Meeting. Minneapolis, Minnesota, 15-16 October 1985. CONF-8510167 (NTIS).

Paisley, M. A., H. F. Feldmann, and W. D. Watt. Wood Gasification Combined Cycle Retrofit in a Conventional Pulp Mill Cogeneration System. American Institute of Chemical Engineers, 1985 Summer Meeting. Seattle, Washington, 25-28 August 1985.

Feldmann, H. F., M. A. Paisley, and H. R. Appelbaum. High-Throughput Conversion of Cellulosic Type Materials to Medium-Btu Gas Without Oxygen. IECEC '85, Miami, Florida, 18-21 August 1985.

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.

Feldmann, H. F. "The Case for Medium-Btu Gas from Biomass." 19th IECEC August 19-24, 1984, San Francisco, California.

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APPENDIX

BIOMASS THERMOCHEMICAL CONVERSION PROGRAM

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