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SERI/TP-622-893

CONF-801130--1

THE COMBUSTION, PYROLYSIS,
GASIFICATION, AND LIQUEFACTION
OF BIOMASS

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MASTER

SEPTEMBER 1980

TO BE PRESENTED AT
ENERGY FROM BIOMASS CONFERENCE
BRIGHTON, ENGLAND
4-7 NOVEMBER 1980

PREPARED UNDER TASK NO. 3356.40

Solar Energy Research Institute

A Division of Midwest Research Institute

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Prepared for the
U.S. Department of Energy
Contract No. EG-77-C-01-4042

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Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price:

Microfiche \$3.00
Printed Copy \$4.00

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THE COMBUSTION, PYROLYSIS, GASIFICATION, AND LIQUEFACTION
OF BIOMASS

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Summary

We can provide all the products now obtained from oil by thermal conversion of the solid fuels biomass and coal. As a feedstock, biomass has many advantages over coal and has the potential to supply up to 20% of U.S. energy by the year 2000 and significant amounts of energy for other countries. However, it is imperative that in producing biomass for energy we practice careful land use.

Combustion is the simplest method of producing heat from biomass, using either the traditional fixed-bed combustion on a grate or the fluidized-bed and suspended combustion techniques now being developed. Pyrolysis of biomass is a particularly attractive process if all three products--gas, wood tars, and charcoal--can be used. Gasification of biomass with air is perhaps the most flexible and best-developed process for conversion of biomass to fuel today, yielding a low energy gas that can be burned in existing gas/oil boilers or in engines. Oxygen gasification yields a gas with higher energy content that can be used in pipelines or to fire turbines. In addition, this gas can be used for producing methanol, ammonia, or gasoline by indirect liquefaction. Fast pyrolysis of biomass produces a gas rich in ethylene that can be used to make alcohols or gasoline. Finally, treatment of biomass with high pressure hydrogen can yield liquid fuels through direct liquefaction.

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1. COAL VS. BIOMASS - THE PAST AND FUTURE ROLE OF SOLID FUELS

Until a little over a century ago, mankind relied on the solid fuels-- biomass (mostly wood) and coal--to supply space and industrial heat, energy for transportation, and power. With the discovery of plentiful, convenient, low cost oil and gas, the use of solid fuels greatly diminished. Now that shrinking gas and oil reserves necessitate a return to the traditional solid fuels, several new factors which favor the use of biomass must be considered in choosing between biomass and coal for various uses.

Wood was the principal fuel of mankind until about 1800, when many nations began to use coal for a variety of reasons. In some cases (England) the wood supply was exhausted by overharvesting. In other countries (the United States) coal was plentiful and could be obtained more cheaply than wood. Coal also has the advantage of being a denser fuel than wood, and it can be stored and transported more conveniently.

Now that we are turning back to solid fuels (reluctantly), this past experience suggests that where possible we will choose coal rather than biomass. However, a number of technical and social factors have changed and can tilt this decision toward wood and other forms of biomass. Coal is now less desirable because we are less willing to tolerate the despoliation of the land associated with mining. We are concerned about contamination of our air and water by the sulfur in coal. We also recognize the possibility that continued use of fossil fuels may upset the CO₂ balance of the atmosphere and our climate. Finally, the race of men willing to toil and moil in the bowels of the earth for pennies a day has disappeared during the era of low cost oil energy.

Biomass, on the other hand, can be obtained on a renewable basis with actual improvement of the land. The techniques for planting and harvesting biomass for fuel are similar to those used for agriculture and forestry; biomass can be produced continuously on a renewable basis as we now produce food, lumber, and paper. Biomass production can be a source of revenues for land improvement. Table I lists six areas where biomass production has resulted in the improvement of the environment.

In the past biomass production has often resulted in land destruction, and Table II is a cautionary list of examples of the destruction caused by unregulated use of biomass for food, lumber, paper, or fuel production. Thus, biomass is a two-edged sword for mankind, and we must learn to produce it only on a renewable basis (1,2).

TABLE I. EXAMPLES OF LAND RESURRECTION

<u>REGION</u>	<u>DATE BEGUN</u>	<u>ACTIVITY</u>	<u>RESULT</u>
Jordan, Syria, Iraq	1970	Dam construction, irrigation, sprinkling	Agriculture being reestablished
Israel	1900	Drainage, irriga- tion, terracing	Productive farms, orchards and forests
China	1950	7% reforestation, shelterbelts halt "sanddragon"	Decreased silting, dust storms reduced, improved forestry
England, Holland	1300	Dyking, pumping	Productive farmland
France (Provence)	1910	Reforestation	Forestry, farming, industry, towns
United States (Kans., Nebr., Colo., Okla.)	1935	Contour plowing, crop rotation, windbreaks	Productive farmland

Biomass is a desirable fuel ecologically because it contains very little sulfur and generally much less ash than coal. With the new agricultural and forestry machines now available, its production is no longer as labor intensive as it was a century ago and the work is certainly less hazardous than mining.

In the past, the principal form of biomass burned for energy was wood because of its relatively high density and availability. The process of densification, in which biomass residues (sawdust, straw, food processing wastes) are compressed into pellets, briquettes, or logs, promises to make other biomass forms, now wasted, equally attractive (3). These processes produce a fuel that has approximately three-fourths of the energy of coal, both on a mass and volume basis, and thus densified biomass could be called "instant coal". A number of plants are now operating in the United States to produce densified biomass.

Thus, though coal will no doubt be the staple solid fuel in many countries, recent technical and social developments favor biomass, and ultimately, when the supply of coal is depleted, mankind will have to learn to

TABLE II. EXAMPLES OF LAND DESTRUCTION

<u>REGION</u>	<u>DATES</u>	<u>ACTIVITY</u>	<u>RESULT</u>
Mesopotamia (Iraq, Syria)	6000 BC to 1200 AD	Canal irrigation and intensive agriculture	Silting and salting - 20 M population at peak, now 3.5 M.
Israel	3000 BC to 100 AD	Agriculture, terracing, grazing	Soil loss through erosion, overgrazing, created hardpan
Phoenecia	4000 BC to 400 AD	Lumbering	Deforestation, erosion
China	3000 BC to 1950 AD	Deforestation, intensive agriculture	Silting, flooding, dust storms
North Africa (Tunis, Algeria)	0 to 600 AD	Corn, wheat, olive production	Erosion, deserti- fication
England	1500 AD to 1700 AD	Lumbering, char- coal manufacturing	Hardpan formation leading to moors, few forests
France (Provence)	1800 AD to 1900 AD	Charcoal manufac- ture to support steel industry	Hardpan formation, high moors
United States (Kans., Nebr., Colo., Okla.)	1900 AD to 1934 AD	Wheat farming	Dust bowl, wind erosion, soil de- pletion, overgrazing

live on its "energy income" because its "energy capital" will be exhausted. A recent analysis of possible energy futures for Sweden suggests that she could rely solely on renewable energy sources, primarily various forms of biomass, and maintain her current standard of living (4). A recent evaluation of U.S. biomass resources suggests that 12 to 17 x 10¹⁵ kJ (12-17 quads) could be obtained from biomass by the year 2000 (2). The potential for biomass production in many other countries is also enormous.

2. COMBUSTION OF BIOMASS

In the past, energy has been produced from wood by simple combustion to produce heat. Combustion now provides about 1.5×10^{15} kJ (1.5 quads) of energy in the United States, primarily from waste liquors from the Kraft paper process, but increasingly from combustion of wood wastes and in home stoves. This combustion is most familiar in the form of a fixed bed of fuel on a grate (or andirons), but we are increasingly turning to fluidized-bed combustion or suspended combustion, which permits cleaner, more automatic combustion in a smaller volume and allows the use of fuel particles as small as sawdust (5). Figure 1 shows a variety of such combustion devices.

3. PYROLYSIS OF BIOMASS

The combustion of wood produces only heat directly (and power indirectly through steam). However, pyrolysis and gasification make possible the production of more refined fuels, which can be used to produce power directly in engines and turbines or for the synthesis of the liquid fuels such as methanol or gasoline on which we have become so dependent.

A familiar experiment in the chemistry laboratory is the heating of a wood splint in a test tube to pyrolyze (rearrange by heating) the wood. A clean combustible gas issues from the mouth of the tube, a brown oil (pyrolysis oil) collects near the cool mouth of the tube, and charcoal remains in the lower portion. In situations where all of these products are needed, pyrolysis processes such as this, on a larger scale, are highly recommended because they are very simple and have a high thruput. A number of pyrolytic processes are being developed (6). Unfortunately, the oil that is produced is corrosive and presents handling problems. Yet ultimately, when we learn how to separate the valuable components of this oil, we may look on it as the most valuable product obtainable from biomass.

The amount of charcoal produced by pyrolysis depends strongly on the rate of heating. If the heat is supplied fast enough, little or no char results, greatly simplifying the subsequent processing. "Fast pyrolysis" processes are discussed in Section 5.

4. GASIFICATION OF BIOMASS

Gasification is the process of treating biomass so that only gas (and sometimes oil vapors) are produced. The charcoal resulting from pyrolysis is converted to gas by partial combustion with oxygen or steam:

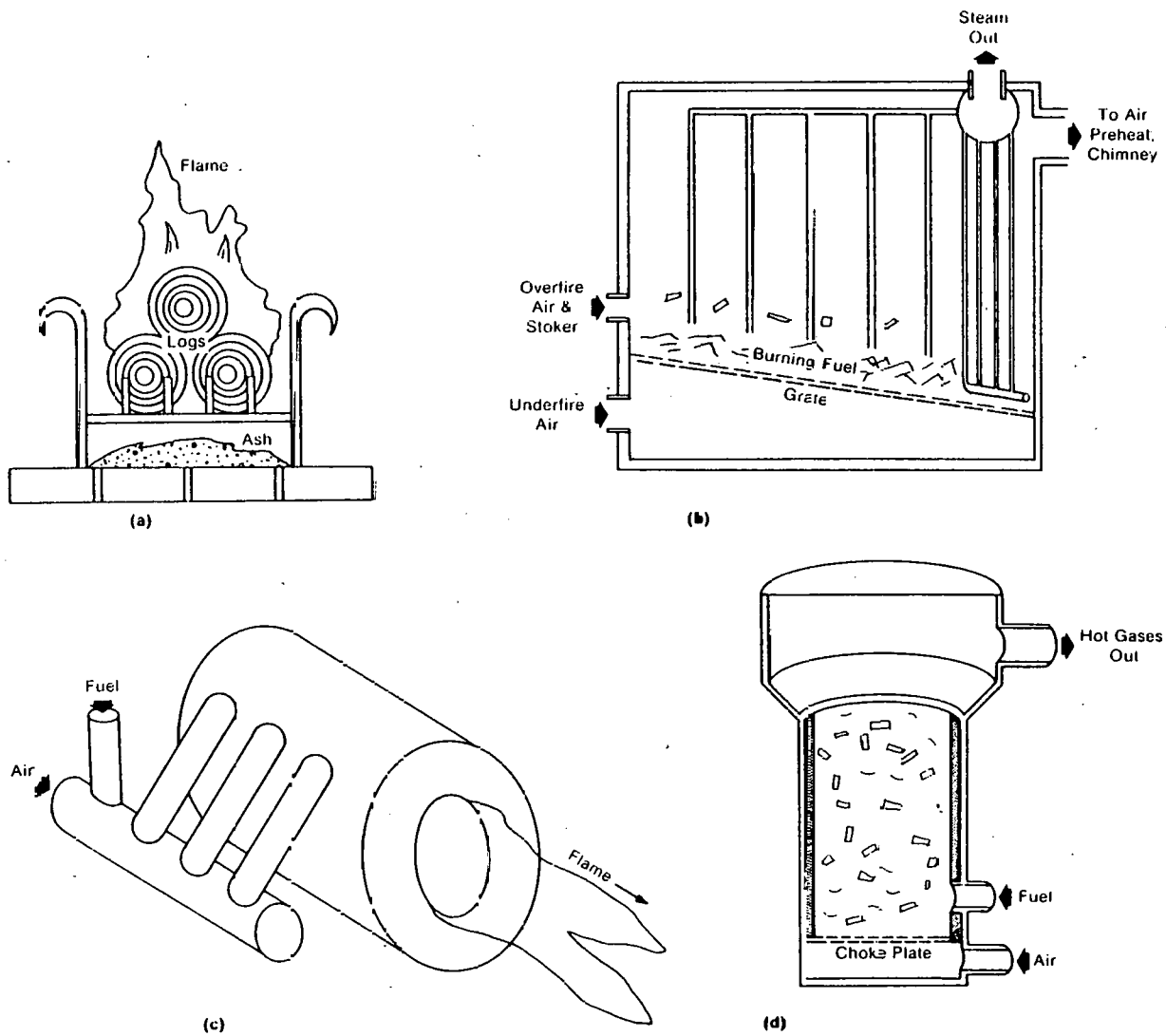
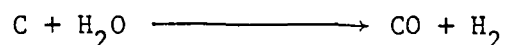
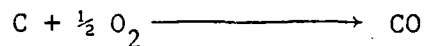


Figure 1. Biomass Combustion Devices. (a) The familiar fireplace provides unlimited air access and poor regulation, control, and heat transfer. (b) Large commercial biomass combustors provide accurate control of air flow and efficient heat transfer to steampipes. Small particles (e.g., sawdust) can be burned in (c) suspension or (d) fluidized-bed combustion units.



This can be accomplished in the updraft, downdraft, fluidized-bed, or suspension gasifiers shown schematically in Figure 2 (6).

In an updraft gasifier for biomass or coal, air or oxygen is injected under a grate supporting charcoal causing combustion and reduction of the gases. The resulting hot gases then rise through the incoming biomass at the top of the shaft furnace of Figure 2, producing oils and water by pyrolysis and drying. The resulting gas must be burned directly (close coupled) because the tars are difficult to remove. Updraft gasifiers are especially appropriate for retrofitting existing gas- or oil-fired boilers. There are now several dozen manufacturers of updraft and downdraft gasifiers in the United States (7).

In the downdraft gasifier air or oxygen is injected above the char mass, causing pyrolysis of the incoming biomass and producing char and oils. These oils then pass over the hot char and are cracked to gases; as a result, very little oil is produced. For this reason, downdraft gasifiers are particularly suitable for running internal combustion engines and over a million were used in Europe during World War II (8).

Although not as well developed, fluidized beds for biomass gasification offer a number of theoretical advantages over the fixed-bed gasifiers discussed above. Because of their very high recirculation rates, fluidized beds have a high heat transfer rate and high thruputs. They are also able to process a wide range of biomass sizes. However, because the contact time is short, they are not as efficient as downdraft gasifiers in consuming char or cracking the oils and tars. There is also a tendency for the light-biomass fraction and lighter char fractions to separate from the bed prematurely. Even less well developed is suspended gasification, though again the suspension gasifier offers high thruputs and the processing of small particles as potential advantages.

When air is used for biomass gasification, a low energy gas [typically 5200 kJ/nm^3 (150 Btu/scf)] results because of the nitrogen dilution. Though suitable for operating engines or close coupling to boilers, it is not economical to distribute this gas in pipelines. When oxygen is used for biomass gasification a "medium energy gas" [typically $10,400 \text{ kJ/nm}^3$ (300 Btu/

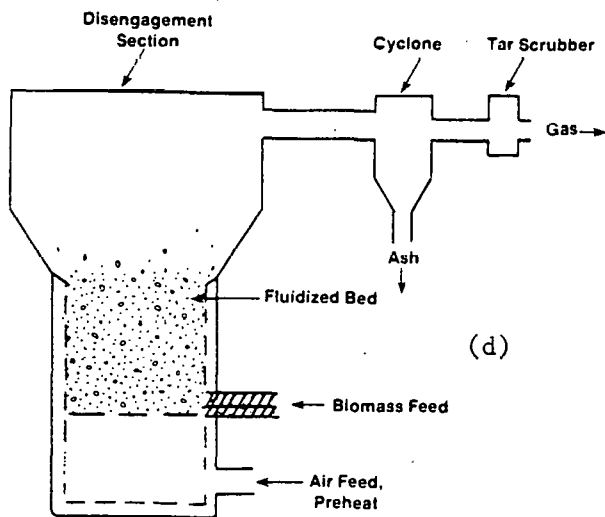
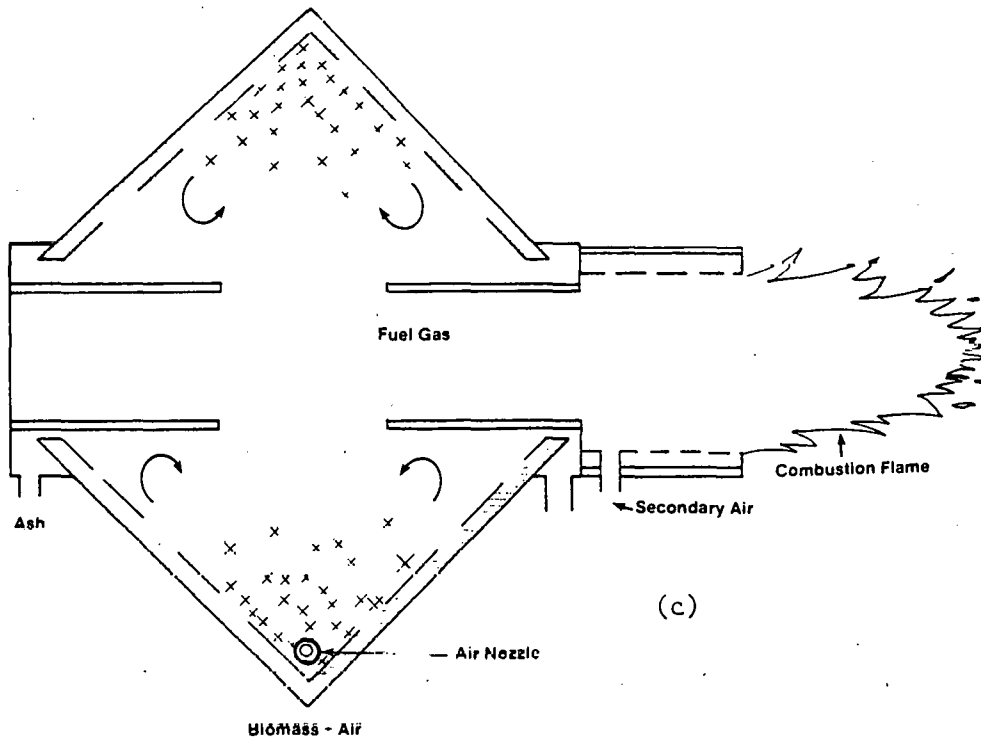
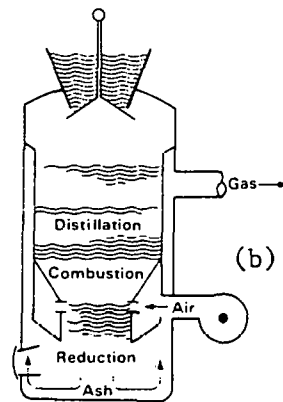
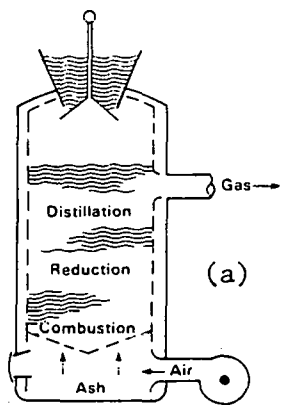


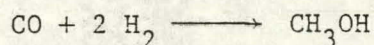
Figure 2. Schematic Diagrams of (a) Updraft Gasifier; (b) Downdraft Gasifier; (c) Suspended-Fuel Gasifier; and (d) Fluidized-Bed Gasifier.

scf)] is produced that can be distributed in pipelines and can be used to power turbines or to synthesize chemicals. We are presently testing the high pressure, downdraft gasifier shown in Figure 3, using oxygen to produce a very clean gas composed of only hydrogen and carbon monoxide.

5. INDIRECT LIQUEFACTION

In many situations gaseous fuels are desirable because they can be distributed by pipeline and are most easily burned with minimum emissions and maximum efficiency; however, gaseous fuels are difficult to store. We will probably require liquid fuels at least for transportation fuels and possibly (depending on cost) for turbine and power plant operation in isolated locations where pipeline costs make gas transport too costly.

Methanol (wood alcohol) was originally made by the destructive distillation of wood, but yields were typically several percent and the major product was charcoal and other chemicals. Now the following reaction is used to make methanol from synthesis gas:



The synthesis gas is compressed to 50-200 atm and passed over a chromium or copper oxide catalyst at 250°-350°C. Synthesis gas is likely to be the key industrial chemical of the post-oil era because, once obtained by gasification of biomass (or coal), it can be used to make methanol, ammonia, gasoline, and many other chemicals and fuels. The gasifier shown in Figure 3 is being developed at SERI especially for the production of fuels and chemicals from biomass.

Other important gases for chemical synthesis are ethylene and other olefins (primarily propylene and butylene). The slow pyrolysis discussed in Section 3 produces oxygenated tars and methane gas. However, it has recently been recognized (7,8,9) that sufficiently high heat transfer rates (typically in excess of 100 W/cm²) induce fast pyrolysis, producing high yields of olefins and often no charcoal at all. Such a process was initiated at the Naval Weapons Center, China Lake, and now is being developed at the Solar Energy Research Institute. High yields of olefins are produced from biomass (typically over 14%). These olefins can in turn be made into plastics (by polymerization), gasoline (by thermal polymerization), or alcohol fuels (by hydration).

SERI Oxygen Biomass Gasifier

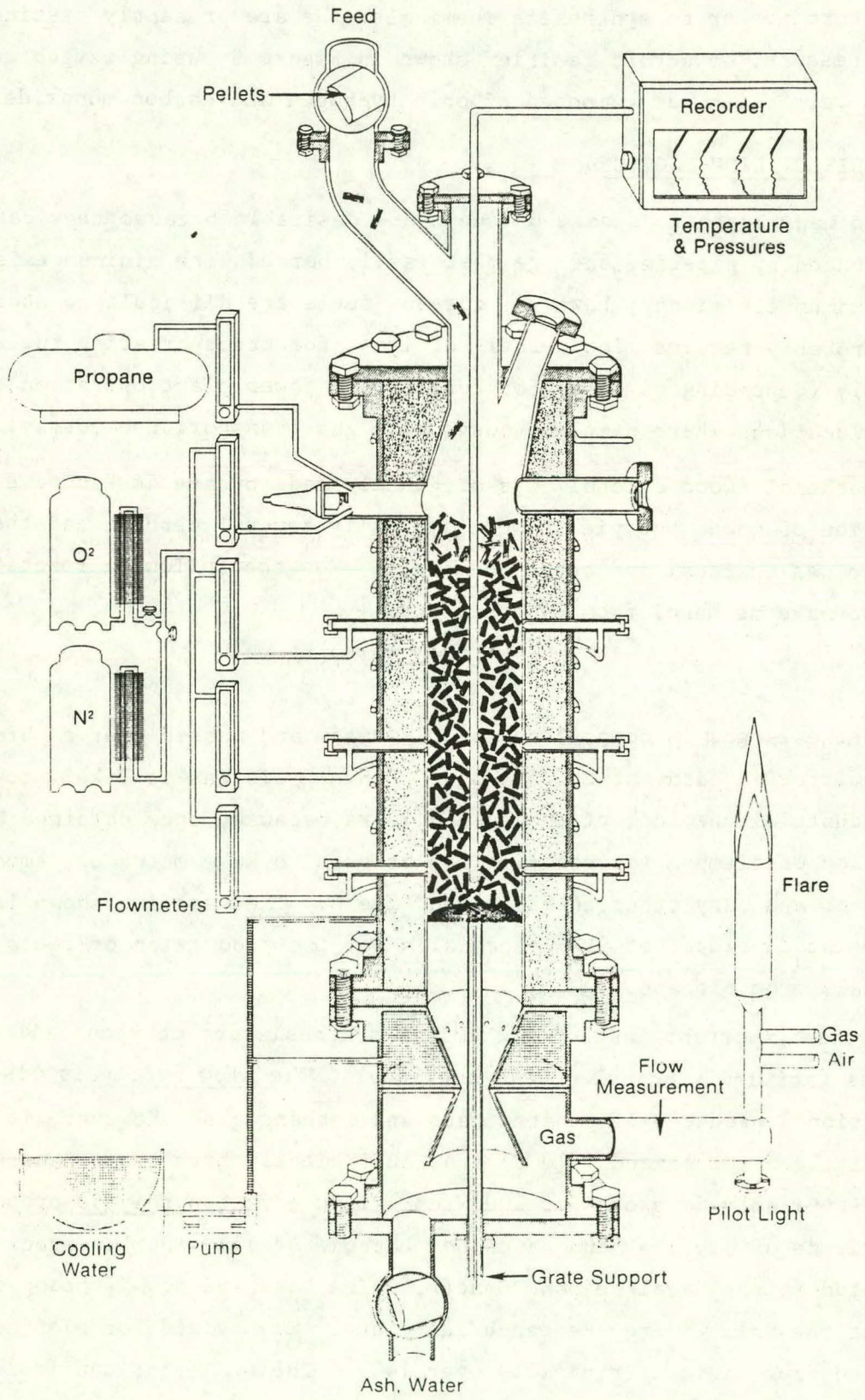


Figure 3. SERI Oxygen Biomass Gasifier

6. DIRECT LIQUEFACTION

It is desirable to be able to convert biomass directly to a liquid fuel, bypassing the gaseous intermediate. In work undertaken during World War II it was demonstrated that alcohols and hydrocarbons could be produced in significant yields by the direct, high pressure hydrogenation of wood or lignin over a catalyst (see Table III)(10). Work along these lines is being pursued now in Canada (11,12). Up to 50 (weight)% of biomass has been converted to oxygenated oils using nickel carbonate catalysts.

TABLE III. EARLY WOOD LIQUEFACTION RESULTS

<u>PROCESS</u>	<u>FEEDSTOCK</u>	<u>PRODUCTS</u>
Hydrogenation	Wood	5% methanol, 15% propanol, 40% pulp
Hydrogenation	Lignin	8% methanol, 13% alcohols, 23% hydrocarbons

More recently, an attempt has been made to apply the methods developed for coal liquefaction to biomass in the "Albany, Oregon" biomass liquefaction process (13). In this process, 30 wt% of biomass is slurried with anthracene oil and heated to 370°C in high pressure (160 atm.) hydrogen or carbon monoxide. A number of difficulties have plagued this pilot plant because the oil does not allow high concentrations of wood to be injected into the reactor. An aqueous pretreatment has permitted higher concentrations of more reactive wood to be used in the reactor and several barrels of oil have been produced with a relatively low oxygen content (13).

Thus it can be seen that the thermal conversion of biomass can follow the various routes outlined here to provide the heat, power, fuels, and chemicals currently produced from petroleum.

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