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EVALUATION OF PROCESSES FOR PRODUCING
GASOLINE FROM WOOD

May 1980

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JBF Scientific Corporation
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EVALUATION OF PROCESSES FOR
PRODUCING GASOLINE FROM WOOD

By

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For

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Office of Policy & Evaluation
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EXECUTIVE SUMMARY

If the United States is to diminish or eliminate petroleum imports, it must pursue (1) conservation, (2) production of conventional fuels from unconventional feedstock sources, and (3) development of unconventional energy production systems. This report discusses the second of these pursuits, with the "conventional fuels" being gasoline and alcohol, and with the "unconventional source" being wood. The assessment has considered (1) the extent to which these processes can contribute to fuel supply, (2) the energy and economic costs involved with these processes, and (3) strategies available to accelerate commercialization if one or more of the processes is judged to be worthy of implementation.

Three processes for producing gasoline from wood have been evaluated. These are described in summary fashion below.

PROCESS ROUTES FROM WOOD TO GASOLINE

<u>Process Developer</u>	<u>Biomass Gasification</u>	<u>Primary Intermediates</u>	<u>Final Step to Gasoline</u>
Naval Weapons Center China Lake, CA (NWC)	Pyrolysis	Olefins	Thermal Polymerization
Arizona State U. Tempe, AZ (ASU)	Fluid Bed Pyrolysis	Olefins; Fischer-Tropsch Liquids	Catalytic Reforming
Mobil R&D Co. Princeton, NJ	(Various Pyrolysis Modes; Mobil Process Begins with Methanol)	Medium Btu Fuel Gas; Methanol	Catalytic Reaction

Technical and economic comparisons among the processes have been made, based on a hypothetical common plant size of 2000 tons per day green wood chip feedstock. In order to consider the entire fuel production process, the energy and cost inputs for producing and delivering the feedstock were included in the analysis. In addition, perspective has been provided by comparisons of the wood-to-gasoline technologies with other similar systems, including coal-to-methanol and various biomass-to-alcohol systems.

Based on several assumptions that were required because of the candidate processes' information gaps, comparisons of energy efficiency were made. Several descriptors of energy efficiency were used, but all showed that methanol production from wood, with or without subsequent processing by the Mobil route to gasoline, appears most promising. It must be emphasized,

however, that the critical wood-to-methanol system remains conceptual. Another observation was that the ethanol production systems appear inferior to the wood-to-gasoline processes.

Each of the processes investigated requires further research and development to answer the questions about their potential contributions confidently. The processes each have so many unknowns that it appears unwise to pursue any one while abandoning the others.

Other evaluations in this report lead to several findings that are briefly summarized here:

- . Product selling prices for biomass-derived gasoline show a wide range of estimates; the lower limits of this range suggest possible competitiveness in the near future with conventionally produced gasoline.
- . If biomass-derived gasoline is commercialized, significant production is not likely to occur for at least 15 years. The types of motor fuel that will be in use after that time are highly uncertain. Biomass-derived gasoline processes should be pursued with this uncertainty in mind.

I. INTRODUCTION

The production of gasoline from wood could lessen the United States' dependence on imported petroleum and non-renewable domestic energy sources. Research groups have been developing chemical process systems, at the laboratory and small pilot plant scale, to convert various organic feedstocks such as wood chips or municipal solid waste to gasoline. These developing process systems use different routes, can operate with different feedstocks, have different energy efficiencies, and yield products with different characteristics.

The purposes of this report are to review the state of the art, and to provide an assessment of the technologies, for deriving gasoline from wood.

All of the methods for producing gasoline from biomass are at an early stage of development, although some are more advanced than others. Energy and cost information on these processes is therefore approximate, and all of the process developers acknowledge this fact.

A description of the systems under development is presented in the next section, followed by detailed assessments of the systems in Section III. These assessments focus on energy efficiency and economics. Section IV applies the results of these assessments to the potential role of wood-derived gasoline. Throughout the report, comparisons of the subject technologies with alcohol technologies appear, so that the relative merits of these potential automotive fuels can be assessed.

II. BACKGROUND

In this section, available information on three innovative systems for making gasoline is summarized briefly. The listed references should be consulted for more detailed descriptions. The section concludes with a description of alcohol production systems.

A. PROCESS DESCRIPTIONS FOR PRODUCING GASOLINE

1. Naval Weapons Center (NWC) Process

A schematic of the overall system proposed by Diebold and Smith⁽¹⁾ is shown in Figure 1. The many inputs and outputs shown give some indication of the system's complexity and the need to optimize operating parameters to attain favorable economics and energy balances.

The product stream of almost every process shown in Figure 1 has a variety of potential uses and markets, each of which has a unique value. For example, the ethylene emerging from the various unit processes may be marketable as a petrochemical feedstock, thereby making available more crude oil for production of gasoline in conventional refineries. In addition, decisions must be made about the best uses for by-product gas streams containing hydrogen, methane, and carbon monoxide. These gases could be used for the system's energy input needs, or they could be marketed.

The state of the NWC system's development does not appear sufficiently advanced to support product mix and product use optimizations. The information that is described here does, however, permit preliminary technical and economic assessment of this overall system for producing gasoline.

The system that NWC has developed relies on a combination of a pyrolysis step that is in an early stage of development and downstream processes that may require less development work because of petroleum refinery experience. Emphasis here is therefore placed on the pyrolysis process.

a. Pyrolysis

The system requires as feed a finely ground and dry organic material. In the bench-scale setup at China Lake, CA, such a feed (200-250 μm) is fed into a fluidized bed chamber. There, the feed is mixed with a carrier gas that transports it into the pyrolysis chamber. This chamber consists of a 3/4 - inch diameter tubular reactor. Reactor lengths of 2 and 6 meters result in pyrolysis times of about 50 and 150 milliseconds respectively. The resulting gaseous stream containing tars, chars, and pyrolysis gases is fed into a cyclone to remove the char. The product stream is then quenched in a hot water bath, which condenses the steam and tars and prevents further cracking of the gasoline precursors. The final step in the pyrolysis subsystem requires a cyclone to remove an oil mist in the product stream before the gases are purified and compressed for polymerization into gasoline.

Notes:

steps for physical cleaning of gases not shown

Figure 1. Simplified Schematic of Naval Weapons Center Process

b. Gas Purification

The pyrolysis gases (at 450 psi) are reacted with hot aqueous potassium carbonate which selectively removes the CO_2 , hydrogen sulfide, and other water solubles. The gas mixtures are then passed through an organic solvent (benzene) which selectively absorbs the desirable olefins. The by-product gases (CO , CH_4 , and H_2) are vented off in the bench-scale system, but would be recovered in a larger plant. The olefin-rich solvent enters a hydrocarbon stripper that heats the solution, driving off the more volatile hydrocarbons. The bottom lean oil (benzene) is recycled into the hydrocarbon absorber.

If the upstream pyrolysis and separation processes can provide a sufficiently clean stream of gases to these purification steps, the purification itself should be relatively straightforward since it is based on established technology.⁽²⁾

c. Polymerization

Like the gas purification steps, polymerization is a demonstrated technology given the proper feed.^(3,4) The purified volatile olefins are compressed to 765 psi and fed into a constant temperature (450°C) polymerization reactor. This reactor consists of a stainless steel tube 3 meters long by 1.3 cm in diameter immersed in a boiling sulfur bath. This sulfur bath acts to maintain a constant temperature to control the exothermic polymerization reaction. The hot product vapors from the polymerization bath are then cooled, condensed and stored. Unpolymerized olefins can be recycled. The conversion yields per pass have been as high as 80 percent. Noncondensable gases are removed and the resulting liquids are reported to have very low viscosities and to yield 90 percent gasoline when distilled. The high temperature boiling liquid fraction yields fuel oil and lubricating oil fractions.

2. Arizona State University Process

Since 1975, Dr. James Kuester and co-workers have been developing a system that can produce gasoline from various organic feedstocks⁽⁵⁾. A schematic of this system is shown in Figure 2.

Like the NWC process, the pyrolysis gases have been shown to be rich in gasoline precursors such as ethylene. Unlike the NWC process, no chemical purification steps for the gases are required. Physical removal of char and tar is required, in addition to a water-gas shift to optimize $\text{CO}:\text{H}_2$ ratios.

a. Pyrolysis

The ASU pyrolysis system uses a dual fluidized bed arrangement. In the bed that serves as a combustor, an inert solid medium is heated. That medium is continuously transferred between the two vessels; it provides the heat to the bed serving as the pyrolysis reactor.

Notes:

Several steps for physical cleaning of gases not shown

Figure 2. Simplified Schematic of Arizona State University Biomass-to-Gasoline Process

The pyrolysis temperature can vary in the 1000-2000°F range, with a slight positive pressure (0-5 psig). Under these conditions, the feedstock is converted to a gas. This gas is cleaned of char and tar before entering a compressor. Some gas is recycled to the pyrolysis reactor to fluidize the bed, while the remainder enters the liquid fuels synthesis system.

b. Liquid Fuels Synthesis

In this process sequence, many by-products are produced. These are not used in the bench-scale system but (as in the NWC process) their value in fueling the system at a larger scale must be considered.

A modified Fischer-Tropsch* catalytic reactor is fed pyrolysis gas. A cobalt-alumina catalyst developed for this purpose at ASU is used. This process also uses a fluidized bed, enhancing temperature control. Reactor temperature and pressure are approximately 300°C and 125 psig. The gaseous product is cooled, yielding (after a physical separation) two liquid products: a hydrocarbon phase and an alcohol-water phase. The hydrocarbon/water ratio is about 10:1 by volume, and the water phase contains about 15 wt. % low molecular weight alcohols. The hydrocarbon phase is paraffinic with some branched compounds, and could probably be tailored to match paraffinic fuels such as kerosene and diesel. To upgrade this fuel's octane (i.e. make gasoline), a catalytic reformer using a fixed bed and a commercial catalyst is used. Reformer temperature and pressure are approximately 400°C and 500 psig.

3. Mobil Research and Development Corp. Process

Mobil has developed a system for conversion of methanol to gasoline^(6,7,8,9). Because methanol can be produced by proven methods from a variety of sources, Mobil has not experimented with production of the methanol feedstock. This process is considered here because methanol can be produced from wood by methods discussed below. (Most of Mobil's publications emphasize coal as the primary source of methanol precursors, but that emphasis does not lessen the technical interest here in biomass sources.) The Mobil process is shown schematically in Figure 3.

In the Mobil process, vapor methanol enters the reactor, and passes through a catalyst bed, where the temperature and pressure are 775°F and 25 psig. (Other reactor temperatures and pressures have been used.) The catalyst was developed by Mobil and is the major unique factor in the system. The catalyst produces a reaction simply characterized as:

*Fischer-Tropsch synthesis is a catalytic process developed several decades ago in Germany to convert synthesis gas to liquid hydrocarbon fuels and water. Synthesis gas is a mixture of CO and H₂, and can be produced from coal or biomass by any of several gasification processes. The ASU modification to the Fischer-Tropsch scheme also converts olefins in the gas stream to liquid fuels.

Figure 3. Simplified Schematic of Mobil Process for Producing Gasoline from Methanol

The products are separated into a hydrocarbon fuel gas phase and liquid hydrocarbon (gasoline) and water phases in the separator and stabilizer systems. Exothermic reactions permit heat recovery in several heat exchangers.

a. Methanol

The source of methanol for the Mobil process can be a coal gasification process followed by a methanol production step. Commercially available and proven processes are available for this route to methanol^(7,10). Of more direct interest to this report, however, is the production of methanol from biomass. One process that yields methanol from a wood feedstock uses a gasification step followed by catalytic conversion to methanol (Figure 4). Another process with many similarities has been under development by Chem Systems, Inc.⁽¹⁰⁾. That process includes a cryogenic separation step upstream of the methanol synthesis, which occurs in a three-stage fluidized bed reactor. These methanol-from-wood systems are conceptual.

B. DESCRIPTION OF PROCESSES FOR PRODUCING ALCOHOL FOR FUEL

In addition to the thermochemical synthesis of methanol (described above in relation to the Mobil Process), alcohol fuel can be produced by the biochemical route described here for ethanol.

1. Ethanol

Fermentation of sugar solutions from grains or sugarcane to produce ethanol is a well established technology. Fermentable sugars can also be produced from wood, by methods that are under development. Wood contains cellulose, hemicellulose, and lignin, all of which complicate the fermentation process. These three types of substances occur in high concentrations in most types of biomass, and can comprise 90 to 95% of a wood feedstock. Cellulose and hemicellulose are polymers, and some of their decomposition (hydrolysis) products inhibit fermentation to ethanol.

Either enzymatic or acid hydrolysis is normally used to pretreat biomass for subsequent fermentation. Acids used include sulfuric and hydrochloric. Process control of hydrolysis is difficult, but considerable research is being funded by DOE in this subject.

A process for production of ethanol from wood is shown schematically in Figure 5. Other cellulosic feedstocks could be converted by the same general scheme, and sugar crops may be fermented without hydrolysis.

Notes:

Physical Separation Processes Not All Shown

Figure 4. Simplified Schematic of a Recent Process Design for Producing Methanol from Biomass

10

Figure 5. Simplified Schematic of Fermentation and Pretreatment Processes for Ethanol Production from Wood Biomass

III. TECHNOLOGY ASSESSMENTS

This section provides analyses of the important economic and energy characteristics of the systems under study. Many of the assessments were necessarily based on assumptions, because of the small scale at which most of the processes of interest have operated. To place the analyses in perspective, therefore, a discussion of each system's principal unknowns is provided first in this section.

A. INFORMATION GAPS

1. Naval Weapons Center Process

The principal uncertainties regarding performance of this process include:

a. Available information is not adequate to support reliable energy balance calculations. Experiments with this process have all been at bench scale. The NWC investigators desire to develop further information at bench scale, but require more funding to do so. Even with this further work, uncertainties will remain because of the large heat losses inherent in bench scale work.

b. The thermal polymerization step has many technical uncertainties. Although developed in the 1930's, this process has been infrequently used in the petroleum industry for nearly 30 years. This lack of use may be caused by the expansion in the 1950's of the market for ethylene and other olefins rather than by obsolescence of the process. In any event, recent experience with the process is lacking; therefore, considerable development is required to quantify its energy balances and to optimize its operation.

c. The pyrolysis system will require much development. At full scale, the system is envisioned as consisting of many (perhaps 20) tubular reactors in parallel. Feeding and transport of equal amounts of biomass through these pyrolysis tubes is a difficult engineering problem.

d. Potential environmental problems are uncertain at this time. Air and water emissions are not characterized with regard to quality or quantity. Costs for environmental controls and siting difficulties are, therefore, not clearly understood.

e. Only a small amount of gasoline has been produced with real biomass feed; this product's volume was not sufficient for octane testing. The product that was tested to 90 octane was polymerized from purchased bottled ethylene.

f. Chars and tars that are removed from the gas stream in aqueous removal systems may not be economically recoverable as process energy sources.

g. Long-term use of the product in automotive engines may cause unforeseen problems.

2. Arizona State University Process

a. Wood sources that may be contaminated with agricultural chemicals may poison the various catalysts in the system.

b. The ability of presently used reformer processes to convert the Fischer-Tropsch product of this process to gasoline efficiently is uncertain. One focus of present research is to improve reformer yield without unacceptably low octane in the product.

c. The pyrolysis system's product should be high in olefin content for the downstream processes to be most effective. Whether olefin yields can be improved is uncertain and is a subject of current research.

d. This process shares the following unknowns with the NWC process:

- . small scale and consequently sketchy knowledge of energy balances;
- . environmental effects;
- . potential for efficient recovery of chars and tars for process energy from aqueous suspensions;
- . performance in engines in the long term.

3. Mobil Research & Development Co. Process

a. The process has not been operated, and is not expected to be tested in the near future, with methanol synthesized from biomass. Moreover, the modern processes for making methanol from biomass have focused on methanol rather than on optimizing the product mix (e.g. by coproduction of SNG). Therefore, energy and economic relationships for the use of biomass feedstocks are not well understood.

b. Mobil believes that more work with coal feedstocks is needed to assure understanding of required feedstock quality. Because biomass sources are so heterogeneous, it is reasonable to infer that specifications for biomass feedstocks will also be difficult to establish.

c. The Mobil process also shares the common unknowns listed above (Part d. under the ASU process). However, many of these unknowns are primarily attributable to the wood-to-methanol system, which is a precursor but not part of the Mobil process.

d. Methanol Production

Although production of methanol from wood was practiced for decades, the processes used were inefficient and methanol production presently relies on other feedstocks. Recent reviews of wood-to-methanol routes have emphasized conceptual systems, because of the reviewers' belief that any future production of methanol from biomass will use advanced technology.

The schematic in Figure 4 is based on an oxygen/steam fluidized bed gasifier that is conceptual. Most wood gasifiers that are available or are being developed operate at atmospheric pressure, but the source of information on this wood-to-methanol route believes that the energy and cost picture of the system is enhanced by a pressurized product from the gasifier⁽¹⁰⁾.

Similarly, the methanol synthesis process was selected by the same source because of expected energy advantages, although that process is also conceptual.

Other reviews of potential wood-to-methanol processes have conceptually paired gasification and synthesis technologies that are being separately developed⁽¹¹⁾. The compatibility of these subsystems has not been demonstrated.

4. Ethanol Production

Although manufacture of ethanol from fermentable sugars is a well-established process, many uncertainties remain relating to the production of fermentable sugars from various types of biomass.

B. NET ENERGY

For any evaluation of a system that produces fuels, knowledge of the relationships among energy content of the feedstocks, energy content of the products, and energy inputs to the system's processes is essential.

In addition to the question of absolute values of energy inputs and outputs, it is useful to consider the form of the energy flows. For example, a process that requires large inputs of fuels derived from non-renewable sources should be so identified when compared with a process that can use a greater proportion of renewable energy inputs.

To quantify both the absolute energy flows and the quality of those flows (i.e. renewable or not), a framework has been developed: the generalized flow sheet shown in Figure 6.

- A = Renewable Energy Input (e.g. wood)
- B = Non-renewable energy required to obtain A (e.g. agriculture, transport)
- C = Energy Content of waste, available
- D = Energy lost in process, unavailable
- E = Nonrenewable energy input required by process
- F = Usable energy produced that is substitutable for nonrenewable sources

Figure 6. Generalized Energy Conversion Flow Sheet

The relationships among these energy flows will be expressed in several ways, none of which alone provides a total understanding. The expressions are defined below, with brief descriptions of their interpretations:

"Efficiencies"

$$\text{Net Thermal Efficiency (NTE)} = \frac{\text{Product out} - \text{nonrenewable in}}{\text{Feed}} = \frac{F-E-B}{A}$$

This parameter measures the net energy conversion of feed into fuel product. NTE ignores the "quality" of the energy, putting raw feed on the same basis as high-quality liquid fuels and electricity, even though the feed has a far smaller diversity of uses.

$$\text{Energy Efficiency} = \frac{\text{Product Out}}{\text{Total Input (including Feed)}} = \frac{F}{A+B+E}$$

This expression also ignores energy "quality". It is less sensitive than NTE to differences in nonrenewable inputs.

. "Ratios"

$$\text{Energy Benefit Ratio, } R = \frac{\text{Product Out}}{\text{Nonrenewable input}} = \frac{F}{E+B}$$

If: $R > 1$, the process yields more renewable energy than it consumes in nonrenewables.

$R < 1$, The process is a net consumer of nonrenewable energy.

Feedstock is not accounted for by this expression, but when comparing systems with a common feedstock flow, it gives a good view of the high-quality energy flow relationships.

$$\text{Net Energy Ratio} = \frac{\text{Product out} - \text{Nonrenewable input}}{\text{Nonrenewable Input}} = \frac{F-B-E}{B+E}$$

This term is simply $R-1$, and is included for the reader's convenience in comparing these assessments with others that have used the Net Energy Ratio.

. Net Energy = Product out - Nonrenewable input = $F-B-E$

Comparisons should include the net amount of Btu yielded by a process, for ease in evaluating energy contributions. This parameter serves that purpose.

1. Basis for Comparisons

A fair comparison among processes should be based on a set of assumptions common to all processes. Unfortunately, previous analyses of the processes under study were based on sets of assumptions unique to each process. Therefore, we have developed a common set of assumptions as a basis for this report. These assumptions are summarized in Table 1.

For comparison purposes, a coal-to-methanol system is considered also. Because coal is nonrenewable, only the "efficiency" terms are appropriate for evaluating this process. Data were taken from a report(9) on the Mobil process, which considered coal gasification by the Lurgi process and methanol synthesis by the Lurgi Low Pressure process.

Table 1. Assumptions Common To All Technologies

Plant Capacity (input)	2000 short tons/day green wood chips*
Feedstock Source	Wood: Harvested, chipped, and transported in trucks with average round trip of 60 miles
Feedstock Higher Heating Value (HHV):	4500 Btu/lb wet

All feedstock input to process; none diverted to fuel process, although some intermediate products may be used as process fuel (therefore $C = 0$ for all processes).

*For feedstocks other than wood, plants were sized on the basis of a feedstock energy content (HHV) equivalent to 2000 tpd green wood.

Values for the energy flows in Figure 6 are tabulated in Table 2. The following discussions describe the bases for the tabulated values.

2. Energy Required to Obtain Wood or Coal

Reports on silvicultural biomass farming⁽¹²⁾ and on recovery, chipping, and transport of logging residues⁽¹³⁾ have been reviewed. Energy consumption of 6.8×10^5 Btu/ton was cited for biomass farming⁽¹²⁾, and 5.7×10^5 Btu/ton for forest residues⁽¹³⁾. For this report, a value of 6×10^5 Btu/ton has been used as the nonrenewable energy required to obtain and deliver green wood chips to the processing plant. Coal extraction and transport energy use has been set at 1.8×10^6 Btu/ton, based on information in an above-cited report⁽¹³⁾.

3. Naval Weapons Center (NWC) Process

A tentative preliminary analysis (unpublished) of the NWC process carried out by Dow Chemical Company, based on incomplete data from laboratory experiments, was conducted for a 100-ton per day Municipal Solid Waste (MSW) feed which would yield approximately 60 tons per day of dry biomass feed.

Table 2. Summary of Process Energy Flows

<u>PROCESS</u>	<u>ENERGY CONTENT (HHV) OR FLOW IN BTU/DAY x 10⁹</u>					
	<u>A*</u>	<u>B</u>	<u>C</u>	<u>D</u>	<u>E</u>	<u>F</u>
<u>Wood to Gasoline</u>						
Naval Weapons Center	18	1.2	0	13.1	1.9	6 gasoline 0.8 oils
Arizona State U.	18	1.2	0	12.2	1.1	6 gasoline 0.85 n-propanol
Mobil R&D Co.	18	1.2	0	10.2	0.4	8.6 gasoline 0.4 fuel gas 0.9 LPG
<u>Biomass to Alcohol</u>						
Ethanol						
- from wood	18	1.2	0	13.6	0	4.4 ethanol
- from grain						
present	18	6.7	0	31.1	23.4	10.3 ethanol
potential	18	3.4	0	12.7	0	5.3 ethanol
- from sugarcane	18	3.4	0	11.3	0	6.7 ethanol
<u>Wood to Methanol</u>	18	1.2	0	7.2	0.2	11 methanol
<u>Coal to Methanol</u>	18**	1.6	0	10.8	3.6	9.5 Methanol 1.3 LPG

* See Figure 6 for identifications of energy inputs/outputs

** For coal, A is nonrenewable, but is shown as a basis for computing energy efficiency. Feed is assumed to be 932 tons/day at 19×10^6 Btu/ton HHV.

a. Grinding and Drying Wood

The Dow analysis considered preparation of MSW; therefore, another data source was required. A report⁽¹⁴⁾ on the wood-to-oil process being developed at Albany, Oregon, provided motor specifications for grinding and drying green wood chips to a flour similar to that required by the NWC process. The information for the Albany plant is approximate, primarily because the units were not sized on the same basis. Values of approximately 5 to 20 horsepower per ton of wood per day were computed from the available data. (Interestingly, preparation of MSW for the NWC Process, as computed from the Dow analysis, required approximately 7 to 13 horsepower per ton per day). For the present analysis, a value of 6 horsepower per ton per day was used. The lower end of the estimated range was favored because of assumed greater efficiency in a production-scale plant. In thermal terms, this value converts to 7×10^8 Btu/day.

b. Processing Wood Flour to Gasoline

A process flow sheet in the Dow review of the NWC process tabulated heating and electrical power requirements. Heat requirements were assumed to be satisfied from recovery and combustion of process sidestreams such as chars and gases. Electrical requirements were approximately 0.8 megawatts. This value was linearly scaled by the ratio of dry organic feedstocks between this and the Dow analyses: 1000/60. The resultant process energy consumption, here assumed provided from nonrenewable sources, is 1.2×10^9 Btu/day. Adding this to the feedstock preparation energy gives a total consumption of 1.9×10^9 Btu/day. NWC investigators have alluded to the possibility that a carefully designed plant may be able to run itself⁽¹⁵⁾. Although available information cannot settle this issue, we assess the case of zero nonrenewable inputs later in this section.

The yield of the NWC process was estimated by Dow at 67.6 gal/dry ton of organic feed. Another source, using the same bench-scale information from NWC, estimated 27.3 gal/dry ton of ground wood feed⁽¹⁶⁾. NWC itself, based primarily on theoretical considerations and literature data for similar processes, estimates a yield of 75 gal/ton dry ash free organic matter. For this report, we have selected 50 gal/dry ton as the yield. This value converts to 6×10^9 Btu/day production of gasoline. Light oils that are also produced by the process are expected to add another 13% to the product mix's total HHV.

4. Arizona State University (ASU) Process

a. Grinding and Drying Wood

No information on pretreatment is available from Arizona State, but the process does not require finely ground feedstock. For this reason, and because much of the NWC process' pretreatment energy use is for grinding wood flour, the ASU process was assumed to require slightly more than half of the pretreatment energy of the NWC process: 4×10^8 Btu/day.

b. Processing Wood to Gasoline

The principal energy consumers in the ASU process are the compressors that pressurize gases for liquid fuel synthesis. Information relating to the energy requirements of the compressors is available from:

- . A process flow diagram for a 10-tpd demonstration plant, prepared by Argonne National Laboratory⁽¹⁷⁾. Data provided with that diagram allowed computations to be made for this report.
- . Data on compression energy use in the bench-scale plant at ASU⁽¹⁸⁾.

Scale-up of these pieces of information led to an estimate of 7×10^8 Btu/day compressor energy use for a 2000-tpd plant. A similar approach was used for the reformer heater, another significant point of energy consumption. The scaled-up value for this unit is 2.8×10^7 Btu/day. The total nonrenewable energy use is estimated as the sum of pretreatment, compression, and reformer heating loads: 1.1×10^9 Btu/day.

The yield of gasoline from the ASU process has been reported, as of late 1979, to be 32 gal/ton cellulose under "present" conditions, and 80 gal/ton under "optimal" conditons⁽¹⁹⁾. For this report, there is no sound basis to predict a yield different from that of the NWC process. Therefore, 50 gal/dry ton wood has been selected. To the gasoline product energy has been added the energy content of the n-propanol by-product, which has generally been approximately 14% of the gasoline's energy content.

5. Mobil Research & Development Corp.

The gasoline production facilities are viewed here as a two-stage system: methanol production from wood, followed by gasoline production from methanol. Each of the two stages has separate battery limits, such that energy recovery from stack gases or other in-process sources can be practiced only with processes within each stage. This approach has been taken because of the form of available information; it is not within the scope of this investigation to design an integrated wood-to-methanol-to-gasoline facility. Therefore, some efficiencies that might be available in an integrated facility may not be accounted for in this analysis.

a. Wood-to-Methanol

Information on the conceptual wood-to-methanol process was available directly, for the 2000-tpd green wood chip plant⁽¹⁰⁾. These data are summarized in Table 2. The product energy yield is high compared to other processes shown on the table, but is supported by an independent source⁽¹¹⁾ that evaluated several potential combinations of wood gasifiers and methanol synthesis technologies, with projected yields and process efficiencies similar to those shown here.

b. Methanol-to-Gasoline

A very thorough report⁽⁹⁾ provides information on several variants of the Mobil process, but all cases developed are of integrated plants with a coal feedstock. Accordingly, information has been developed from an earlier Mobil report for DOE⁽⁸⁾, emphasizing the methanol-to-gasoline process separately. Although the product mix can be optimized to meet a variety of market conditions (as with other processes reviewed here), it appears that emphasis on gasoline production would yield 1 gallon of gasoline from 2.4 gallons of methanol⁽⁸⁾. With this type of yield, the energy content of by-products (fuel gas and LPG) should be approximately 13% of the total product output (HHV). The values for parameter "F" in Table 2 were derived from these figures, with all of the output from the methanol plant being the input to the Mobil process.

The value for nonrenewable energy consumption is the sum of that needed in the methanol plant and that needed in the methanol-to-gasoline plant. This latter value was derived from an energy balance in the above-cited Mobil report⁽⁸⁾, scaled linearly to the common plant size being considered here.

6. Ethanol

To provide a consistent basis for comparison, processes being developed to produce ethanol from a wood feedstock have been reviewed. In addition, a review of the recent literature on ethanol production from grain and sugarcane has led to process energy estimates for these types of biomass.

a. Wood Feedstock

Yields of ethanol from wood using either acid hydrolysis or enzyme hydrolysis to produce fermentable sugars have been estimated in the range of 0.06 to 0.23, expressed as a weight fraction⁽²⁰⁾. Most reviews have selected the range 0.14-0.16^(21,22,23), and 0.16 has been used here. The process is considered able to run itself, with residues being used to produce the required process energy⁽²¹⁾.

b. Grain (Corn) Feedstock

Two conditions have been assessed: present technology, and a system adjusted for a more favorable energy balance through extensive use of crop residues as process fuel. The values have been derived from a recent review article that used data commonly cited in the literature⁽²⁴⁾. The hypothetical "potential" case shown in Table 2 is as uncertain as the wood-to-gasoline processes primarily because of presently unquantified effects of removing large amounts of crop residues from the land.

c. Sugarcane Feedstock

The data used were from a recent paper by Hopkinson and Day dealing with likely conditions in Louisiana⁽²⁵⁾. The results are much less favorable than an earlier paper⁽²⁶⁾ on Brazilian conditions, where yields are similar but

agricultural energy inputs are lower than in the U.S. Three cases were assessed in the Hopkinson and Day paper:

- . converting all bagasse to steam and producing surplus energy (Case 1);
- . converting enough bagasse to meet the processing plant's needs (Case 2);
- . burning fossil fuel to meet the industrial plant's needs (Case 3).

Case 2 was used here.

7. Energy Comparisons Among Systems

Table 3 summarizes the various expressions of energy efficiency that were introduced with Figure 6. Several observations are offered below, but all must be tempered by the fact that every process for wood-to-gasoline conversion is in the developmental stage. Future developments may produce significant changes in any of the values.

- . On the basis of all expressions used, methanol production from wood, with or without subsequent processing by the Mobil route to gasoline, appears most promising.
- . For the NWC and ASU routes to gasoline, the "efficiency" criteria are not strongly affected by the process' use of nonrenewable energy (E). However, if the feedstock's energy content is ignored as it is in the net energy and in the "ratio" parameters, the value selected for E is very important. Presently, very little basis exists for estimating the value of E reliably.
- . The only process that consumes more energy than it produces is the present production system for grain alcohol.
- . All of the ethanol systems appear inferior to the wood-to-gasoline processes, with the possible exception of wood-to-ethanol. The primary reason for the wood feedstock's advantages relative to other feedstocks for ethanol is the lower agricultural/transport energy input.

C. COST COMPARISONS

Because this report discusses future energy technologies, some of which are conceptual, the bases for cost estimation are not firm. Preliminary estimates are available, however, for all of the processes discussed here. These estimates have been adjusted for this report to reflect common assumptions related to feedstocks, plant sizes, and inflation.

1. Bases for Estimates

The flow sheets and other process characteristics described previously are the basis for all estimates, at the 2000-tpd green wood chip feed plant size.

Table 3. Summary of Values for Processes' Energy Conversion Efficiency

	Net Thermal Efficiency	Energy Efficiency	Energy Benefit Ratio	Net Energy (Btu/day)	Net Energy Ratio
<u>Wood to Gasoline</u>					
Naval Weapons Center	0.21	0.32	2.2	3.7×10^9	1.2
(-If process can run itself)*	(0.31)	(0.35)	(5.7)	(5.6×10^9)	(4.7)
Arizona State U.	0.25	0.34	3.0	4.6×10^9	2.0
(-If process can run itself)*	(0.31)	(0.36)	(5.7)	(5.7×10^9)	(4.7)
Mobil R&D Co.	0.46	0.50	6.2	8.3×10^9	5.2
<u>Biomass to Alcohol</u>					
Ethanol					
(from wood)	0.18	0.23	3.7	3.2×10^9	2.7
(from grain - present)	-1.1	0.21	0.34	-19.8×10^9	-0.7
(from grain - potential future)	0.11	0.25	1.6	1.9×10^9	0.6
(from sugar- cane)	0.18	0.31	2.0	3.3×10^9	1.0
<u>Wood to Methanol</u>	0.53	0.57	7.9	9.6×10^9	6.9
<u>Coal to Methanol</u>	0.31	0.47			

*Values in parentheses were computed assuming that zero nonrenewable process energy input (E) could be achieved.

Other bases include:

- . Mid-1979 dollars
- . Economy of scale factor for capital investment = 0.65
- . Detailed breakdowns on which these estimates were based came from the same sources as the flow sheets in Section II.
- . Feedstock (green wood chips) cost \$15/ton.

2. Estimates

Comparisons of capital investments, operating and maintenance costs, and product costs are shown in Table 4. The refinery gate costs shown are based on a regulated venture with a ratio of debt-to-equity capital of 65:35. Straight-line depreciation over 20 years was used. These and other financial parameters are the same as those used by Kohan *et al.* (10). A nonregulated venture with private capital would generally require a larger return with consequent higher product costs.

Sources of cost estimates and further notes of explanation appear in Table 5.

3. Confidence in Estimates

Economic and technical analyses of eighteen biomass energy options have been assessed by Kam *et al.* (27). For each option, costs and product revenue requirements have been estimated with "base case", "low," and "high" values. For costs and revenue requirements, the variation between the low and base case estimates is typically 25% of the base case value. The difference between base case and high values is typically 50% of the base case value. The cost estimates presented in this report have similar degrees of uncertainty.

Table 4. Approximate Comparison of Costs Among Processes

	Capital Invest- ment	Annual O&M (Includes Depreciation)	Return on Rate Base & Income Tax	Total Annual Revenue Required*	Annual Output (Btu x 10 ¹²)	Price at Plant Gate (\$/MM Btu)	Annual Output (Gal x 10 ⁶)	Price at Plant Gate (\$/gal)
<u>Wood to Gasoline</u>								
Naval Weapons Center	55	16.8	4.7	21.5	2.5	8.60	21**	1.02**
Arizona State U	75	14.7	6.4	21.1	2.5	8.44	21**	1.00**
Mobile R&D Co.	135	37	12	49	3.6	13.61	30.4	1.61**
<u>Biomass to Alcohol</u>								
Ethanol (from wood)	175	44	15	59	1.6	36.88	20	2.95
<u>Wood to Methanol</u>	120	35	10	45	4	11.25	62.7	0.72
<u>Coal to Methanol</u>	255	40	22	62	3.9	15.90	61	1.02**

All values in millions of dollars (mid-1979) unless otherwise noted.

* 20-year average.

** Approximations based on gasoline-equivalent (or methanol-equivalent) Btu for multi-product processes.

Table 5. Sources for Cost Estimates

<u>Process</u>	<u>Source(s)</u>	<u>Remarks</u>
NWC	Dow (unpublished), (16)	
ASU	(17)	Source cost did not include reforming. Assumed values based on the Mobil process (in both systems, this final catalytic step amounts to about 10% of total wood-gasoline cost).
Wood-Methanol	(10)	
Wood-Methanol-Mobil	(10), (8)	Processes simply added. An integrated facility may achieve lower selling price.
Wood-Ethanol	(28)	

IV. POTENTIAL ROLE OF WOOD-TO-GASOLINE TECHNOLOGY

This section discusses probable future trends in the production and use of wood-derived automotive fuels. The discussion includes the total mix of fuels, because the demand for any one fuel (e.g. gasoline) affects that for all other fuels being used in highway vehicles. One aspect of this discussion is the potential development of automotive engines that can burn fuels with octane requirements lower than today's gasolines. Production aspects (as opposed to demand influences) are restricted to gasoline and alcohol in this report.

The factors examined in this section include:

- . Feedstock sources and availability
- . Potential supply contributions in 1985 and 2000
- . Commercialization
- . Other factors: Proprietary Rights; Environment

The gasoline/alcohol comparison will be made primarily on the basis of ethanol manufacturing and blending. Although methanol is another possible blending agent, methanol has several inherent characteristics which make it less desirable as a fuel in the near term⁽²⁹⁾.

A. FEEDSTOCK SOURCES AND AVAILABILITY

The future contributions of biomass-derived fuels obviously depend on adequate feedstock supplies. Recent estimates for these supplies for 1985 and 2000 are presented for various biomass resources in Table 6.

The types of feedstocks required for either pyrolysis or hydrolysis and fermentation will depend strongly on moisture content in the feedstock. For example, some pyrolysis processes require a very dry feedstock, although the allowable moisture depends on the specific process. Hydrolysis and fermentation on the other hand can readily use feedstocks with high moisture content and can thus potentially use all the biomass resources listed in Table 6. The process is only limited by the extent to which the cellulosic materials (e.g. wood and agricultural wastes) may be hydrolyzed into fermentable sugars. To attain high conversion efficiency of cellulose, extensive milling and size reduction are required.

On the basis of the above discussion, Figure 7 presents an overview of current and future production routes for converting the biomass resources to either gasoline, ethanol, or methanol.

Figure 7. Process Routes for Gasoline or Alcohol Fuels from Biomass Feedstocks

Table 6. Quantities of Maximum Biomass Resource
for Conversion to Liquid Fuels

(Quantities in 10^6 dry tons per year)

<u>Resource</u>	Amount Available in:	
	<u>1985</u>	<u>2000</u>
Wood	464	549
Agricultural Residues	220	278
Grains	38	23
Sugars	8	172

Source: Ref. (30)

These resources must be considered in view of conversion efficiencies so that potential fuel production can be described. Such a description appears in Table 7, leading to gallons of fuel that can be produced in 1985 and 2000. This information is normalized to energy production figures in Table 8. Based on the available projections used in developing Tables 7 and 8, it appears that the energy production potentials of gasoline and alcohols are similar. This is a statement about potential supply only, however. Demand factors exert a very strong influence on the potential role of any candidate fuel, and they are discussed below.

B. POTENTIAL SUPPLY AND DEMAND FACTORS IN 1985 AND 2000

The maximum potential supply, assuming use of all available biomass to produce automotive fuels, was discussed above. Lesser levels of supply, and reasons therefor, are discussed here.

The future demand for biomass derived liquid hydrocarbon fuels in the years 1985 and 2000 depends strongly on several interrelated factors. These factors include:

- . availability of petroleum and attendant costs
- . refinery capacity and flexibility in processing crude petroleum and syncrudes
- . future mix of vehicles for transportation (e.g. demand factors related to fuel composition, performance and cost)
- . competition from liquid fuels derived from coal or oil shale.

The total supply system for liquid fuels essentially includes four resources. They are petroleum, oil shale, coal, and biomass. The recent price increases in crude petroleum are beginning to allow the higher cost fuels derived from oil shale, coal, and biomass to be more competitive. Large investments in incipient technologies are required to implement such synthetic fuels programs, however.

1. Demand Factors for Gasoline and Broadcut Fuels

On the demand side, future technological developments in vehicle engines and attendant fuel requirements may alter the present demand patterns for automotive fuels. As presented in Table 9, many of the new engine developments will require a much lower quality fuel than is currently demanded. That is, such fuels as alcohol, distillates, diesel oil and other broadcut fuels may be more in demand as these new engines penetrate the transportation market. These future vehicles will be able to use a variety of fuels having no octane or cetane requirements. The conclusions reached by a recent study conducted by Jet Propulsion Laboratory for DOE summarize some of the main points (31).

Table 7. Potential Volume Production of Automotive Fuels

	Year	Dry Feedstock Available (dry ton/yr)	x Conversion Efficiency (gal. product/ dry ton feed)	= Gal. Product per year
1. Gasoline from Wood (NWC, ASU, Mobil)	1985	464×10^6	40 to 80	$19 \text{ to } 37 \times 10^9$
	2000	549×10^6	40 to 80	$23 \text{ to } 46 \times 10^9$
2. Methanol from Wood	1985	464×10^6	140 to 180	$65 \text{ to } 84 \times 10^9$
	2000	549×10^6	140 to 180	$77 \text{ to } 99 \times 10^9$
3. Methanol from Coal*	1985	143×10^7	140 to 180	$200 \text{ to } 260 \times 10^9$
	2000	143×10^7	140 to 180	$200 \text{ to } 260 \times 10^9$
4. Ethanol from Wood	1985	464×10^6	40 to 80	$19 \text{ to } 37 \times 10^9$
	2000	549×10^6	40 to 80	$23 \text{ to } 46 \times 10^9$
5. Ethanol from All Feedstocks	1985	730×10^6	50 to 100	$37 \text{ to } 73 \times 10^9$
	2000	1022×10^6	50 to 100	$51 \text{ to } 102 \times 10^9$

Note: With the exception of the coal feedstock, each calculation above assumes complete commitment of available biomass to one fuel. Volume and energy values are, therefore, not to be added, but are mutually exclusive.

* More coal than that shown can be made available, but the value shown represents enough feedstock to provide all of the nation's automotive fuel.

Table 8. Potential Energy Yield of Biomass-Derived
Automotive Fuels in 1985 and 2000

1985

<u>Fuel</u>	<u>Gallons</u>	<u>Btu/Gallon</u>	<u>Btu</u>
Wood-Derived Gasoline	19 to 37 x 10 ⁹	125,000	2.4 to 4.6 x 10 ¹⁵
Alcohols			
Ethanol (Wood)	19 to 37 x 10 ⁹	80,000	1.5 to 3.0 x 10 ¹⁵
Ethanol (All Feed-stocks)	37 to 73 x 10 ⁹	80,000	3.0 to 5.8 x 10 ¹⁵
Methanol	65 to 84 x 10 ⁹	64,000	4.1 to 5.4 x 10 ¹⁵

2000

Wood-Derived Gasoline	23 to 46 x 10 ⁹	125,000	2.9 to 5.8 x 10 ¹⁵
Alcohols			
Ethanol (Wood)	23 to 46 x 10 ⁹	80,000	1.8 to 3.7 x 10 ¹⁵
Ethanol (All Feed-stocks)	51 to 102 x 10 ⁹	80,000	4.1 to 8.2 x 10 ¹⁵
Methanol	77 to 99 x 10 ⁹	64,000	4.9 to 6.3 x 10 ¹⁵

Note: Each calculation above assumes complete commitment of available biomass to one fuel. Volume and energy values are, therefore, not to be added, but are mutually exclusive.

Table 9. Fuel Requirements for Various
Automotive Engines

Engine Type	Fuel Requirement	Fuel
Uniform-charge Otto	High volatility; high octane number, 90-95	Gasoline, alcohols
Honda CVCC Ford PROCO		
Diesel	Cetane number 40-65	Diesel oil
Direct-injected stratified-charge	None ⁽¹⁾	Wide-cut distillate
Texaco TCCS C-W rotary		
Spark-assisted diesel		
Brayton Stirling	None	Wide-cut distillate

(1) The fuel injection and ignition systems for these engines can be designed to use fuels with a wide range of characteristics, but the systems must be specially engineered with the characteristics of the fuel to be used in mind.

Source: Ref. (31)

"It is clear that engines which yield high fuel economy in a vehicle and also can use wide-cut distillate fuels will be particularly attractive from an overall energy efficiency (resource-to-wheels) point of view. Brayton, Stirling, and direct-injection stratified-charge engines fall into the high energy-use-efficiency group using the alternative resources, but the conventional diesel engine does not because of its requirement for relatively high quality fuel (cetane number in a narrow range)."

While the future vehicle fleets may use a variety of fuels derived from renewable resources, the actual impacts of these developments is contingent upon current research and development. For example, some future engines require further technical developments in the use of ceramic materials in engine components. Thus, future vehicle fleets and resulting fuel requirements depend upon the ability to overcome specific technical obstacles to eventual mass production. Another factor in market penetration is air quality. These developing engines are not well understood in this regard. Table 10 presents recent projections of when the new types of engine designs may be available for production.

The diesel and stratified charge engines, according to the cited Jet Propulsion Laboratory Study, appear to be the earlier penetrators. These engine designs would be available in the 1980-2000 time period. Therefore, the fuels (Table 9) for these engines may be in increased demand at a rate depending upon fuel economy, driving habits and the market penetration of these engines.

To estimate these future demands for gasoline, diesel and broadcut fuels, DOE's Alternative Fuels Utilization Program sponsored a study that identified probable automotive fuels composition in the 1985-2000 time period⁽³²⁾. Although several simplifying assumptions limit the quantitative reliability of these projections, Table 11 presents that study's projected demands for gasoline, diesel and broadcut fuel for the 1985-2000 time period. This penetration of broadcut fuels is based on estimates projecting 20% of the total automobile and 20% of the light duty truck vehicle fleets will be using a stratified charge or other advanced engine design in 1985.

These projections are related to alcohol fuels and potential biomass-derived supplies after the following discussion of demands for alcohol fuels.

2. Demand Factors for Alcohol Fuels

From Table 11 the 1985 and 2000 total fuel demands are projected to be 114 billion gallons per year and 155 billion gallons per year, respectively. A national commitment to use of 10% alcohol fuels (gasohol) would affect these projections in various ways, depending on the actual share of gasoline (as opposed to broadcut and diesel fuels) in the automotive fuel market. If the estimates in Table 11 prove to be correct, and if a gasohol program is in place, fuel grade alcohol use would total 5.6 billion gallons per year in 1985. If the penetration of broadcut fuels is not significant, alcohol use for gasohol could be in the 1.0 to 1.1 billion gallon per year range.

Table 10. Summary of the Current Status and Projected Availability
of Various Alternative Automotive Engines

Engine	Current Status	Availability of Required Component Technology	Prototype Development	Production for Market
Diesel	Production	-	-	-
Diesel (turbocharged)	Prototype	Now	Now	1980
Stratified charge (direct injection)				
34 Reciprocating (TCCS)	Laboratory testing	Now	1980-85	1985
Rotary (C-W)	Laboratory testing	Now	1980-85	1985
Brayton (metal)				
2-shaft	Laboratory testing	Now	1980-85	1985
Single-shaft	Engineering studies	Now (except for CVT)	1980-85	1985
Brayton (ceramic)				
2-shaft	Materials R&D	1985	1985-90	1990
Single-shaft	Materials R&D	1985	1985-90	1990
Stirling (metal)	Laboratory testing	Now	1980-85	1985
Stirling (ceramic)	Materials R&D	1985	1985-90	1990

Source: Ref. (31)

Table 11. Projections of Demand for Various Automotive Fuel Types in the Future

	(Billions of gallons per year)	
	<u>1985</u>	<u>2000</u>
Broadcut	19	65
Gasoline	56	39
Diesel	39	51
Total	114	155

Source: Ref. (32)

Table 12. Comparison of Projected Supplies and Demands for Fuels
(Billions of Gallons per Year)

	<u>1985</u>	<u>Ethanol for 10% Gasohol</u>
	<u>Gasoline</u>	
Demand	120*	12
Max. Possible Supply (Table 7)**	37	73
	<u>2000</u>	
Demand	140*	14
Max. Possible Supply (Table 7)**	46	102

Note: * JBF estimate

** Assumes commitment of biomass resources to one fuel. For example, the 1985 supply of biomass-derived fuel could yield either 37 billion gals. of gasoline or 73 billion gals. ethanol.

Predicting whether a demand for this amount of fuel grade alcohol will actually develop requires consideration of the same factors as for gasoline. Alcohol in a gasohol blend, if a commitment to gasohol is made, would simply be used at 10% of the gasoline consumption rate.

3. Synthesis of Supply/Demand Factors

Table 12 compares projections of demand with projections of supply for gasoline and alcohol, based on the above discussions. Biomass availability limits the amount of demand that can be satisfied for gasoline, but not for ethanol in a 10% gasohol mix.

This discussion of supply and demand has considered maximum supplies based on feedstock availability, and probable demands. In the 1985 and 2000 time periods, an even more important factor is the nation's ability to install the required production facilities. This is discussed next.

C. COMMERCIALIZATION

1. Introduction

In considering alternatives to petroleum derived liquid fuels there is a competition among sources (MSW, biomass, and coal) and products (gasoline and gasohol and fuel oils). The different processes which are candidates for commercialization use either a single feedstock or a variety of feedstocks, and generally produce a single type of fuel product. This ties in the commercialization potential of a process with the availability of feed material and with end product demand, which are dependent on transportation costs and projected engine characteristics. Development of two or more processes that used biomass and produced gasoline and alcohol would provide a good likelihood of making an effective alternative liquid fuels contribution by the year 2000. The following discussion develops some of the important considerations in selecting processes for development to full scale commercialization. Since each process selected will go through several development cycles and scales of size before full commercialization, the risk can be reduced in that a particular process may be abandoned for economic or technical reasons at any point in the development process.

2. Reaching the Demonstration Stage

There are generally several steps which must be followed to reach a full scale or near full scale demonstration stage. In terms of wood or other biomass feed quantities, these steps may be characterized as follows:

- . Bench stage - much less than 1 TPD (ton per day)
- . Pilot plant stage - 10-20 TPD
- . Demonstration stage: 100-300 TPD
- . Commercial stage: 300-3,000 TPD (or higher)

The controlling factor in how many development stages are required or in how long it takes to reach demonstration and commercialization is the maximum ratio which can be allowed in production capacity between successive stages by "good engineering practice". If this ratio is too large, the likelihood of encountering severe technical or economic problems in the new stage may be greater than acceptable. If the ratio is too small, valuable development time and money are wasted. This allowable maximum ratio is often chosen to be in the range of 2.5 to 5.0.

3. Selection of Full Scale Plant Size

a. Economy of Scale vs. Transportation Cost

Generally larger plant capacity results in lower product cost, an effect known as "economy of scale". The effect is more dramatic in going from a small to a medium size capacity, and tends to level out as capacity becomes very large. In the cases of interest here, the advantages of large process plant size must be balanced against the increasing transportation costs to bring the biomass from greater distances to meet plant feedstock needs. It is therefore important, in projecting the size, economics and commercialization potential of a specific process, to include the nature and geographic distribution of the feedstock material and the transportation costs involved.

If one assumes a goal for the year 2000 of 10% of the nation's gasoline being supplied from wood, 14 billion gal/yr will be required. With an average plant size of, say, 4,000 wet tpd yielding 100,000 gal/day of gasoline, approximately 380 processing plants would be needed.

4. Financing Requirements

A 4,000 TPD (wet) plant producing 36 million gallons per year of fuel could cost in the range of 80 to 160 million dollars in capital investment. The 380 plants discussed above could involve a total capital requirement by the year 2000 of 30 to 60 billion dollars, or 1.5 to 3 billion dollars per year. This type of financing could be assisted by government incentives such as loan guarantees and tax credits. For example, the Alternative Fuels Demonstration Program being developed by DOE pursuant to PL 95-238 would provide loan guarantees up to 75% of the estimated construction cost of facilities converting non-petroleum feedstocks to useful fuels.

The magnitude of such a development program may be placed in perspective by comparing it to central station power plant capital requirements which are in the order of one billion dollars for a 1,000 MW plant. Thus, the construction of a limited (10%) wood-based synthetic fuels capability could be comparable to building 1 to 3 power plants per year, or increasing the national electric power generating capacity by approximately 0.5% per year.

It is useful to note the uncertainties in capital cost estimates for plants designed to produce liquid fuels from non-petroleum sources. A review of several recent reports was conducted in this study, and revealed the following ranges of estimates:

<u>Fuel</u>	<u>Range of Capital Cost Estimates for Commercial Scale Plants (\$/gal/year)</u>
Liquid Fuels (primarily gasoline from Biomass)	1.7 - 1.9 (Estimated by developers of processes) 2.6 - 4.5 (Estimated in this study)
Liquid Fuels (primarily gasoline) from Coal	3.0 - 4.7
Ethanol	1.6 - 1.9
Methanol	1.0 - 4.0

Another fact to keep in mind is the tendency of capital cost estimates to grow as more is learned about a new fuel conversion process. A study of successive estimates of capital cost requirements for "pioneer" synfuel projects⁽³³⁾ found that these estimates increased at an average rate of 30% per year. These caveats also affect the confidence that can be placed in the product cost estimates given in Section III.

5. Timing

In an implicit way, the above discussions have neglected the fact that a new industry cannot be installed immediately. Design, procurement, and installation of equipment of the type required involve long lead times. Experience must be gained in early demonstration plants so that revised design and operating procedures can be identified and implemented in later facilities.

DOE's Market Oriented Program Planning Study (MOPPS) considered these factors in 1977, and set a maximum allowable growth rate of 35% annually for a new fuel-producing industry⁽³⁴⁾. A more recent study for alcohol fuels by MITRE Corp. used this growth limit to project future production levels⁽³⁵⁾. With a startup of two facilities in 1982, this reasoning led to a maximum of 19 plants in 1985 and 90 in 1990. These plants would supply methanol sufficient for a 5% national gasohol program in 1990. Similar (if not greater) limits to growth can be expected for a new biomass-derived gasoline industry.

Therefore, in the near term, the limiting constraint on contributions from biomass-based fuels appears to be lead time in developing a new industry rather than the more straightforward factors of feedstock availability and market demand.

D. OTHER FACTORS

1. Proprietary Rights

The three processes for gasoline production discussed here are all covered to various degrees by patents or patent applications. Rather than probing the legal and technical details of each patent (Mobil has "dozens" for its process⁽³⁶⁾)

it is more appropriate here to discuss the likelihood that licensing disagreements might be an impediment to commercialization.

If a process has potential for efficient and economic production of gasoline, its development will be pursued primarily by the private sector (if it is economic but not necessarily energy-efficient) or primarily through government incentives (if it is efficient but not necessarily economic). Those who would commercialize the process, if other groups hold patents, will probably approach the holders of the patents to negotiate licensing agreements. It appears likely that such agreements could be reached, adding up to 5% to the selling price of the fuel.

Given the energy problems that this country faces, it appears highly unlikely that any worthwhile process could be impeded seriously by patent considerations. Of course, the primary purpose of the patent system - fostering innovation - should not be frustrated in any commercialization action. Therefore, one equitable course of action in case of a disagreement among private parties may be for the Federal Government to intervene, by holding harmless the commercialization venture and agreeing to defend any suit brought by the patent holder. Because the government is immune from an injunction in a case such as this, the probable outcome would be a court-ordered payment by the Federal Government in lieu of royalties. This course of action can be viewed as simply another incentive for commercialization of processes that appear to be in the national interest.

2. Environmental Effects

Because the biomass-to-gasoline processes have been tested only on a small scale, their environmental effects are poorly understood. All three of the processes (NWC, ASU, and Mobil) will have air emissions, wastewaters, and solid residues of uncertain quantity and quality. It is probably valid to assume that processing plants using these processes would pose environmental problems no more severe than similarly sized coal liquefaction or oil shale processing facilities. Environmental and socioeconomic constraints on such synthetic fuel plants were reviewed in the recent "Environmental Analysis of Synthetic Liquid Fuels"⁽³⁷⁾. That study found "no absolute environmentally related constraint" to development, but noted the uncertain effects of "yet-to-be-defined" regulations.

Another severe environmental constraint may arise from the harvesting activities, especially for standing timber. As Table 6 showed, wood will constitute most of the biomass potentially available in 1985 and 2000, and its harvesting would be on an unprecedented scale with poorly understood effects on forest ecosystems.

E. SUMMARY OF FINDINGS

The process evaluations, and the policy implications thereof, are summarized here. Because many of the processes considered are not well-developed, this report is more of an evaluation than a policy guide. As more is learned about these processes, a firmer base for policy will develop.

1. Process Evaluations

a. Technical

All three processes to make gasoline from wood (including methanol synthesis, whether the methanol is used as fuel or as gasoline precursor) have significant technical uncertainties. Each route also has significant potential. Continued development of the NWC and ASU processes should resolve the many open questions about each process. Development of an economic wood-to-methanol process would offer a high potential payoff, because this route followed by the Mobil process presently appears very efficient in energy terms but very costly in dollar terms.

The technology for ethanol production from sugars is established, but preparation methods must be refined for unconventional feedstocks to expand the resource base.

b. Economic

Refinery gate prices for the gasoline and alcohol fuels discussed here show a wide range of estimates. It appears that biomass-derived gasoline may be less expensive than alcohol fuels on a cost per Btu basis. Either gasoline or alcohol from biomass feedstocks is more expensive than the present cost for gasoline production from petroleum, but this difference can be expected to decline (and, in some cases, to favor wood-derived gasoline) as crude oil costs continue to rise.

c. Commercialization

Fuel alcohol production for gasohol could be commercialized in the early 1980's and could yield a 5% gasohol blend nationally in the early 1990's if aggressively pursued.

If no major technical or procedural obstacles are encountered, wood-derived gasoline might have its first commercial demonstration in the late 1980's. If this industry's growth rate were similar to that projected above for fuel alcohol, it might produce 5 to 10% of the nation's gasoline by the year 2000.

These projections are contingent upon gasoline's continued role as the primary automotive fuel. Significant penetrations of diesel or broadcut fuels would decrease the need for gasoline and gasohol, favoring fuels with less rigid product specifications.

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