JPL PUBLICATION 79-9

Bioconversion Study Conducted by JPL

Sponsored by the Director's Discretionary Fund, Fiscal Year 1978

Compiled by the JPL Bioconversion Technical Committee
and Reviewed by the JPL-Caltech Steering Committee

(NASA-CR-158228) BIOCONVERSION STUDY CONDUCTED BY JPL (Jet Propulsion Lab.) 124 p HC A06/MF A01 CSCL 10A

N79-19450

Unclas

G3/44 16384

November 15, 1978

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

CONTRIBUTING AUTHORS

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1 - IV	SYNOPSIS, INTRODUCTION, CONCLUSIONS, RECOMMENDATIONS Dr. J. J. Kalvinskas Dr. B. O. Stokes
V.	BIOMASS SOURCES Dr. K. Grohmann
VI.	CHEMICALS FROM BIOMASS Dr. M. N. Sarbolouki
VII.	THERMOCHEMICAL CONVERSION OF BIOMASS TO FUELS Dr. C. J. Wallace
VIII.	BIOLOGICAL CONVERSION OF BIOMASS TO FUELS AND CHEMICALS Dr. D. M. Taylor Dr. G. R. Petersen Dr. B. O. Stokes
IX.	BASIC BIOCONVERSION SCIENCES Dr. B. O. Stokes Dr. M. N. Dastoor

ABSTRACT

The Jet Propulsion Laboratory of the California Institute of Technology conducted a study of bioconversion as a means of identifying the role of biomass for meeting the nation's energy fuel and chemical requirements and the role and means for JPL-Caltech involvement in bioconversion. The study was directed and carried out by an interdisciplinary group of JPL and Caltech scientists and engineers and included a comprehensive review of the state of biomass technology through an extensive review of literature sources, and interviews with organizations and authorities active in the field of bioconversion. The bioconversion study included the following categories: biomass sources, chemicals from biomass, thermochemical conversion of biomass to fuels, biological conversion of biomass to fuels and chemicals, and basic bioconversion sciences. General conclusions of the study were that biomass promises to be a significant alternate energy source and that JPL-Caltech have an important role in this technology. A detailed review is included of the bioconversion fields cited with specific conclusions and recommendations for future research and development and overall biomass system engineering and economic studies.

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SECTION I

SYNOPSIS

JPL conducted a study of bioconversion under the Director's Discretionary Funds (DDF) as a means of (1) identifying the role of biomass for meeting the nation's energy, fuel and raw material requirements and (2) identifying the role and means for JPL-Caltech involvement in bioconversion. The study was directed and carried out by an interdisciplinary group of JPL and Caltech scientists and engineers and included a comprehensive review of the state of biomass technology through an extensive review of literature sources, and interviews with organizations and authorities active in the field of bioconversion. The interdisciplinary group consisted of a Steering Committee comprised of both JPL and Caltech staff and a Technical Committee of JPL scientists and engineers. The list of participants is included separately in Table 1.

The bioconversion study was divided into the following sections:

- Biomass Sources
- Chemicals from Biomass
- Thermochemical Conversion of Biomass to Fuels
- Biological Conversion of Biomass to Fuels and Chemicals
- Basic Bioconversion Sciences

Each section included the following: Technical description, economics, potential energy contribution, funding sources and conclusions. Supporting detail for each of the given sections is to be found in the appendixes.

An overall summation of the technical sections is provided by the Introduction, Conclusions and Recommendation sections; proposals and concept papers that have been submitted to funding agencies for consideration are listed in Table 2.

The second year of bioconversion activity under DDF funding will concentrate on several specific areas to allow a more concentrated program development as a means of securing outside support in terms of both funding and joint collaboration. Specific scientific and engineering thrusts in bioconversion will relate to both the JPL-Caltech capabilities and resources as well as the identified areas. An overall need appears to exist for generating a "biomass economy" model that could serve as a blueprint for a comprehensive exploitation of biomass to the fullest for energy, fuels and chemicals. JPL's capabilities for conducting such a study program are very good.

Exploration of key scientific and engineering areas as well as evaluating the larger "systems modeling" effort will be made by the preparation and submittal of concept papers to the major funding agencies for bioconversion that have been identified.

Table 1. Study Participants

The Bioconversion Study consisted of a Steering Committee composed of Caltech and JPL members to provide a general guidance and direction as well as a review of the ongoing effort and a Technical Committee for carrying out the designated activities outlined under the DDF. The personnel and attendant affiliations are outlined below.

Steering Committee

J. J. Kalvinskas, Ph.D. (Chairman)	Supervisor, Chemical Processes Group, Section 345, JPL
J. F. Bonner, Ph.D.	Professor of Biology, Campus
W. F. Corcoran, Ph.D.	V.P. for Institute Relations, Prof. Chemical Engineering, Campus
H. M. Schurmeier	Assistant Laboratory Director, Energy and Technology Applications Office, JPL

Technical Committee

B. O. Stokes, Ph.D. (Leader)	Senior Scientist, Section 345, JPL
M. N. Dastoor, Ph.D.	Senior Scientist, Section 345, JPL
K. Grohmann, Ph.D.	Senior Scientist, Section 345, JPL
J. A. Hanson	Acting Supervisor, Application Analysis and Systems Engr., Section 345, JPL
J. Moacanin, Ph.D.	Deputy Manager, Section 346, JPL
G. R. Petersen, Ph.D.	Senior Scientist, Section 345, JPL
M. N. Sarbolouki, Ph.D.	Senior Scientist, Section 346, JPL
D. M. Taylor, Ph.D.	Supervisor, Life Sciences Research Group, Section 345, JPL
C. J. Wallace, Ph.D.	Group Leader, Chemical Processes Research, Section 345, JPL

Table 2. Proposals and Concept Papers Prepared Under the First Year Bioconversion Program

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Proposals

1. "Biochemical Analysis of the Genetics of Photosynthesis using Protoplast Fusion Techniques," submitted to U.S. Department of Agriculture.
2. "The Role of Energy in Nitrogenase Regulation *In Vivo*," submitted to U.S. Department of Agriculture.
3. "Conversion of Cotton-Seed Hulls to Activated Carbon," submitted to J.G. Boswell and Company.
4. "Genetic Construction of Bacterial Strains for Ethanol Production," submitted to U.S. Department of Energy.

Concept Papers

1. "Development of Hybrid Bioconversion Processes," prepared for U.S. Department of Energy.
2. "Production of Butadiene and Methylethylketone by a Bacterial Fermentation of Polysaccharides followed by a Chemical Conversion," submitted to U.S. Department of Energy.
3. "Genetic Engineering for the Improvement of Methanogenesis," submitted to Gas Research Institute.

SECTION II

INTRODUCTION

As domestic reserves of oil and gas continue to deteriorate, the need to develop alternative energy resources and production technologies grows more acute. While coal and nuclear power appear to be primary energy sources of the future, the potential contribution of several important technologies, including bioconversion, have not received due attention.

Bioconversion is the production of fuels, energy and raw materials using biological processes. The area as presently defined does not include fossil resources of biological origin nor the production of food or lumber. The area is very broad in scope and includes: 1) biomass production from land, fresh water, and ocean farming, 2) conversion of biomass to energy and chemicals through both biological and physical-chemical processes, 3) utilization of waste materials of biological origin (i.e., urban and agricultural wastes), and 4) direct production of chemicals or fuels using biological processes (i.e., biophotolysis and natural rubber production).

The ultimate potential of biomass energy production depends upon the area available for biomass growth. Approximately 200-300 million acres suitable for a yield of 5-10 dry tons per acre per year appear to be currently available for biomass growth. This area could produce a quantity of biomass equivalent to 16-48 quads (1 quad = 10^{15} BTU) or 21% to 64% of the current U.S. energy consumption. Annually renewable urban, agricultural, and forestry wastes are equivalent to an additional potential of 10-11 quads (13-15% of current U.S. consumption). If fully realized, land farming and waste utilization could clearly provide a major portion of the current U.S. energy requirements. Available area for fresh water farming (90 million acres) is included in the land farming estimates. While vast areas are presumably available for development, the potential contribution of ocean farming to the nation's energy supply cannot be adequately assessed until further development activity is conducted in this area. The vast areas of ocean surface are largely unproductive (analogous to land deserts) due to a lack of nutrients and the realization of a large potential from ocean farming is expected to require substantial technological development. It is likely that whatever the contribution may be, it will be far in the future.

While substantial amounts of energy can be obtained through direct burning of biomass the development of practical and economical technologies for the conversion of biomass to gaseous and liquid fuels is required to realize the full potential of biomass energy. Methane, H_2, syngas and ethanol are currently being emphasized as end products due to the versatility and conventionality of gaseous fuels and the suitability of ethanol as a transportation fuel. The conversion of biomass to chemicals can account for only a small portion of the biomass potential. The energy content of all chemicals derived from petroleum feedstocks is only 1.5 quads (about 2% of U.S. usage). Ammonia production, which consumes about 0.7 quads, should receive the primary emphasis in this area

Another crucial factor in the utilization of biomass is economics. Very little firm economic data exists for biomass utilization and projections are often controversial. Environmental restrictions increasingly assist the economics of waste utilization. For this reason, several processes for deriving energy from wastes are developed to pilot scale and are likely candidates for early development. Widespread development in any area will, of course, depend on developing sound economic data.

The field of bioconversion suffers from a lack of basic scientific and engineering development. Until very recently little attention was devoted to the selection, development and management of the optimal biological species for energy production. The development of agricultural techniques, equipment and advanced technologies for the production and conversion of biomass to energy has also been neglected. The basic science disciplines of photosynthesis, biological nitrogen fixation and microbial energy metabolism have not kept pace with the health related disciplines. While this lack of development is definitely inhibitory to progress in this area, a note of optimism is found in the promise of undiscovered potential which awaits a serious development of bioconversion resources.

SECTION III

CONCLUSIONS

The major conclusions derived from the study are listed according to the following sections:

A. Biomass Sources

B. Chemicals from Biomass

C. Thermochemical Conversion of Biomass to Fuels

D. Biological Conversion of Biomass to Fuels and Chemicals

E. Basic Bioconversion Sciences

The technical discussions and details relating to the conclusions are included in the Technical Sections and Appendixes.

A. Biomass Sources

(1) Sufficient land acreage (over 300 million acres) with adequate rainfall (over 20 inches per year) is available east of the Rocky mountains to provide up to 60% of the nation's current energy requirements.

(2) Biomass wastes, if fully utilized, could provide 5 to 10% of the nation's energy requirement in place of the current 1 to 2%.

(3) Large ocean surfaces afford the potential of large biomass production if the engineering and economic problems of ocean farming, harvesting and conversion can be overcome.

(4) Substantial engineering and scientific research and development is required to provide commercially attractive processes for conversion of biomass to energy production.

(5) A major modeling study is required to fully assess the requirements, engineering feasibility and economics of making a massive shift to biomass as a source of energy within the continental United States.

B. Chemicals from Biomass

(1) Chemicals from biomass represent only a small fraction of the national energy consumption. Fuels from biomass represent a larger energy contribution.

(2) Chemicals production from biomass will require extensive research and development, substantial plant investment and dependable supplies of biomass as chemical feedstocks.

(3) The expansion of biomass-derived chemicals will probably rely on the expansion of current areas of specialty items derived from biomass rather than on any new assignment of biomass.

(4) Ammonia production from biomass should receive attention since it represents the single largest consumer of natural gas feedstocks and shows a potential of attractive economics.

C. Thermochemical Conversion of Biomass

(1) A wide variety of thermochemical processes can convert biomass to gaseous, solid and liquid fuels and to usable energy. However, a great deal of uncertainty exists on the engineering, economics and scale-up of the processes for commercial application in the United States.

(2) Applications of thermochemical conversion processes have been primarily on waste materials. Although the technology can be generally applied to other biomass sources, specific engineering developments are required on biomass materials that are to be considered.

(3) A uniform basis of evaluation must be considered in comparing thermochemical conversion processes in order to obtain a valid comparison of yields, efficiencies and economics. This has not been done to date in any significant manner.

D. Biological Conversion of Biomass

(1) Biological processes are characterized by being highly specific, having mild reaction conditions, slow reaction rates and being difficult for scale-up.

(2) Key products are methane and ethanol, which are currently marginally economic in production from biomass.

(3) Specific attention should be directed to photosynthetic organisms (algae and higher plants) for direct production of fuels and chemicals.

E. Basic Bioconversion Sciences

(1) Techniques of tissue culture, in vitro selection, plant regeneration and newly emerging techniques of genetic engineering are expected to provide new strains of plants and microorganisms that will benefit the production of biomass and conversion to fuels and chemicals.

(2) Improved understanding of photorespiration and the basic photosynthetic processes are expected to provide increases in

photosynthetic efficiencies and plant yields that will assist the production of biomass sources.

(3) Biological nitrogen fixation is extremely important in current agriculture. Extending biological nitrogen fixation to cereal grains could be very beneficial in decreasing the need for fertilizer and highly developed nitrogen fixing crops may be required for economical production of energy from biomass.

(4) Biophotolysis is conceptually attractive as a direct route to the production of energy through the production of O_2 and H_2. Much research and development is required to separate the O_2 and H_2 products and to stabilize the biological processes.

SECTION IV

RECOMMENDATIONS

JPL-Caltech should actively seek to develop a firm technological base in bioconversion. Biomass has the potential of becoming a significant alternate energy source to existing fossil fuels and nuclear energy without requiring major scientific and engineering breakthroughs. JPL and Caltech have existing scientific/engineering capabilities and interest that reflect a potentially strong contribution to the field. Specific areas of endeavor that should be considered are:

(1) Engineering and scientific development of thermochemical and biological conversions of biomass to fuels and chemicals.

(2) Genetic engineering applications to biomass production and conversion processes.

(3) Basic research in photosynthetic processes to obtain increased plants yields.

(4) Systems engineering and modeling of bioconversion.

(5) Engineering/scientific support of Caltech activity in ocean farming.

An overall assessment of JPL-Caltech capabilities and organizational strength suggests that the Laboratory should assume a strong leadership role in the bioconversion sector. The current study has confirmed that large quantities of biomass are potentially available within the continental United States to provide a substantial alternate energy source. However, the blueprint for obtaining that energy in an economic fashion is lacking. A great many scientific, engineering, legal, geographical, economic, political and national questions must be answered and resolved to obtain a "biomass economy" that will effectively function. JPL could clearly fill the leadership role by conducting such a national study. A strong recommendation is that JPL-Caltech pursue such an assignment.

SECTION V

BIOMASS SOURCES

A. BACKGROUND

Biomass sources under the current usage of the term are organic wastes and cultivated biological (primarily plant) matter (1,2). Cultivation of biomass by land, ocean and fresh water farming are currently being considered for the production of energy. These areas are briefly described below.

1. Wastes

Organic wastes can be derived from several sources, which form the basis for their division into the following categories: municipal solid waste (abbr. MSW), sewage, animal manure, crop residues, forest (and associated industry) residues and other industrial residues.

The research activities in the areas of waste utilization for energy production are concentrated on conversion processes with very limited activity in the area of collection and storage. This can be explained by the presence of established industries catering to needs in the areas of collection, transportation and storage of materials.

2. Energy Farming

Land farming is in the most advanced stage of all three forms of biomass farming. This stems primarily from the fact that land farming and forestry are huge, well established industries. The production of biomass for fuel is a reasonable alternative from the standpoint of net energy gain. The energy input/output ratios for production and harvest of whole plants range from 1:12 for herbaceous annuals to 1:25

for trees (silviculture) (3). Considerable research has been done in this field under the auspices of the U.S. Department of Agriculture. It should, however, be pointed out that the historical thrust of this research has been the production of food and fiber and not the production of energy. A systematic research program, dealing with production of energy via land farming, was established relatively recently under the sponsorship of the Fuels from Biomass Branch (FFB) of U.S. Department of Energy. The research carried out under the program concentrates mostly on silviculture (tree farming) and culture of sugar yielding herbaceous plants, such as sugar cane (see Appendix A, Table A-1 for the FY 77 list of funded programs).

Silviculture seems to have a leading edge because the following arguments speak in its favor: high energy output/input ratio (3), cost of production is in the lower range of estimates (4), and wood makes an excellent fuel which is low in ash and sulphur, relatively low in moisture and reasonably dense and storable(4). Silviculture plantations would also minimize erosion problems in comparison with other options, since the period from planting to harvesting is several years. When coppicing is practiced, the roots are left in the ground for many years and thus help to stabilize the soil. High yielding tree species, such as sycamore, poplar, alder and eucalyptus are currently being tested for their suitability for intensive cultivation (4,5). In some cases improved strains were produced by genetic manipulations (5). As the next step, a 1000-acre demonstration tree plantation will be established at Savannah River, Georgia, in the near future (6,7).

While the primary emphasis of land farming is on silviculture, considerable research is also being carried out in the culture of herbaceous plants. The great diversity of herbaceous plants makes them suitable for cultivation in the areas unsuitable for silviculture (e.g., marshes). Their yields are in some cases very large and they are often better suited for conversion into secondary fuels (such as ethanol). The current research activities in this area are concentrated on the cultivation of plants which accumulate high concentrations of sugar (sugar cane, sweet sorghum and sugar beets) (see Appendix A, Table A-1). Their primary application is the production of ethanol. Dr. M. Calvin is also investigating cultivation of plants which store part of their energy in polymerized hydrocarbons (see Appendix A, Table A-1).

Fresh water farming for energy is still in the research stage. The current research is concentrated on microalgae and floating angiosperms, such as water hyacinths (see Appendix A, Table A-2). The main attraction of these plants is their high potential yield under optimal conditions (8). There are several projects currently funded by the Fuels From Biomass Branch of DOE that explore the feasibility of obtaining energy from algae grown on waste materials (such as sewage) (see Appendix A, Table A-2).

The farming of macroalgae in the open ocean is another option which can provide not only energy but also food and chemicals. The prime algae candidate is giant kelp (Macrocystis Pyrifera). After several years of laboratory studies, a 0.1 acre module kelp farm will be built in the near future by General Electric under DOE funding (6). Other species of algae have the potential for cultivation (6,9) but have not been studied as well as kelp.

B. POTENTIAL ENERGY CONTRIBUTION

The current contribution of biomass to the U.S. energy supply was estimated at 1.8 quads/year in 1977 (10). This contribution represents about 2% of the current U.S. energy usage and is comparable in magnitude to the contribution of nuclear power plants. Practically all of this energy is derived from the utilization of wastes with the largest single contributor (55% of total) being wastes from the pulp and paper industries (10). While the potential of biomass energy has been projected at 7 quads (5-10% of the national usage) by the year 2000 (4, 7) a much larger maximum potential is apparent. As indicated in Table 3 the maximum potential of wastes is around 10-11 quads (13 to 15% of current U.S. requirements); the probable maximum potential for land farming is 16 - 48 quads (21-64% of current U.S. requirements); and the maximum potential of energy from ocean farming, while presently unknown, could be vast. The sum of biomass energy from all sources does have the potential to provide a substantial portion of the U.S. energy requirements. The realization of this potential will require a major national effort, and solutions to technological and social-economic problems involved in biomass utilization.

1. Wastes

Table 3 shows the current availability,cost and energy content of the U.S. waste resource.

2. Land Farming

Several independent studies(3,4,11) dealt with the availability of land for plant farming for energy production (detail in

Table 3. Biomass Wastes Availability and Costs

Type of Waste	Amount Generated (10^6 dry tons/yr)	Considered Available (10^6 dt/yr)	Energy Content (quads)	Cost Per Unit[a]	Cost per 10^6 BTU
Forest Industries[b] & Logging Wastes	334[e]	300[c]	4.8	\$1-60/DT[d]	\$0.06 - 3.74
Crop Residues	332[e]	248[e]	4.0	\$30-45/DT[f]	\$1.87 - 2.81
Municipal Solid Waste	135[g]	135[g]	1.2	Negative[h]	Negative[d]
Manure	210[i]	30[e]	0.2	0 (at the source)[j]	0 (at the source)[j]
Industrial Organic	60[i]	60[i]	0-2 0-5	Possibly negative	Possibly negative
Sewage Sludge	20[i]	20[i]	0.3	Negative	Negative
Totals	1,081	793	10.7-11.2		

[a] Comparative costs for fossil fuels are:

Oil Heavy = \$12.13/bbl (\$2.00/10^6 BTU)
Natural Gas = \$1.50/1000 cu ft. (\$1.50/10^6 BTU)
Coal - \$20-50/Ton (0.83-2.08/10^6 BTU)

[b] Trend in paper and pulp industry toward larger utilization of tree biomass may considerable diminish the amount of logging residues (Ref. 19).

[c] References 12 and 13.

[d] Compiled from Ref. 12. Wide span is caused by the diversity of the waste group. Logging residues themselves are considered to have a zero value at the source, but collection and transportation fees account for the cost.

[e] Reference 14.

[f] Reference 21.

[g] References 15, 16, 17 and 20.

[h] Negative cost means that disposal fees are extracted from the sources and can be used to subsidize the conversion process.

[i] Reference 18.

[j] Zero at the source means that no value is attached to the residue.

Appendix B, Tables B-1 and B-2). Their general conclusion was that about 200-300 x 10^6 acres, primarily located east of the Rocky Mountains, could be used for this purpose. The major criteria for the site selection were: the amount of rainfall, land slope, soil class and growing season, as well as its current utilization as forest and pasture land (Appendix B, Figure B-1). This area would be about 10-15 percent of the total land area of the conterminous U.S.(22). If we assume a yield of 5-10 DT of biomass/acre/year--this is comparable to the yield of currently cultivated plants (23,24)--and an average energy content of 8000 Btu/lb(12) of dry plant biomass, the area designated above could provide 16-48 quads of energy a year. This amount of energy could satisfy 21-64 percent of our current energy needs, if conversion efficiencies comparable to those of fossil fuels were obtained. If concentrated effort in this area would increase this yield, the same amount of energy could be derived from smaller acreage or more energy could be obtained from the same acreage.

Another important consideration is the cost of biomass obtained from land farming. The estimate ranges from \$20-30/DT (3,25)in the case of silviculture and \$20-55/DT (3,6) for culture of herbaceous plants. That represents \$1.25-3.4/10^6 BTU, which would put land cultivated biomass at less than or up to twice as expensive as fossil fuels.

3. Fresh Water Farming

The Dynatech Report (8) estimates that 95 x 10^6 acres of U.S. land are potentially available for fresh water farming (this includes land which would be flooded for this purpose). Since the estimate is based on the basis of land which would be withdrawn for potential biomass production via fresh water farming and not on the area which is covered by water already, it will compete directly with land farming. Therefore, the potential contribution of fresh water farming is, in fact, included in the estimates for land farming. This potential energy source is still, to a great degree, in the R&D stage and estimates for various schemes are usually based on theoretical extensions of laboratory experiments.

Dynatech (8) in its report analyzed the economic considerations for one such system and concluded that unless the large yields could be obtained (approximately 20 DT/year-acre or more), the fresh water farming for microalgae would be more expensive than land based systems. The special application for fresh water farming is in secondary treatment of sewage, where their fast rate of nutrient removal is being employed.

4. Marine Farming

This area, also in the R&D stage, is another potential large contributor to the U.S. energy supply. With an estimated 1.6 billion acres of area within the 200 mile wide coastal zone (26) there is a possibility of devoting sizable acreage to farming for energy, food and other products. To estimate correctly the potential contribution of this source to the U.S. energy supply is presently impossible, because we do not know how much of the area could be actually utilized. The division into competitive uses, such as fishing, oil and gas exploration, shipping lines, etc., is not accurately known. Also, potential for farming the open ocean, beyond the national boundary lines, is hard to assess, especially from a legal point of view.

However, to have an idea of the potential of this source, by just devoting approximately 100 x 10^6 acres of our available ocean surface to kelp farming, we could have a source of about 20 quads of energy at 20 DT/acre/year. There is a current controversy concerning the practicality of one such scheme (i.e., growing kelp on artificial floating platforms) where proponents claim that the cost of production would be roughly on par with land based systems and opponents claim that the costs would be prohibitive and the system energy inefficient. Until the experimental evidence from the 0.1 acre model farm is obtained, it will be difficult to decide the issue.

C. SOURCES OF FUNDING

The primary governmental program which funds the cultivation of plants for production of energy is the Fuels From Biomass Program of DOE (see Appendix A, Tables A-1 and A-2 for levels of funding in FY 77). Other agencies which fund certain aspects of biomass production are NSF, USDA, EPA, and NOAA of the Department of Commerce. NOAA is primarily funding projects in aquaculture.

D. CONCLUSIONS

1. Wastes

We can derive a significant portion (5-15%) of our energy needs from utilization of our waste materials. The research effort in the area of waste as an energy resource should concentrate on collection, processing and conversion. Since wastes are produced as by-products, their production is a function of other processes and will be dictated by needs other than energy.

2. Land Farming

Land farming can supply a large portion of U.S. energy needs (possibly as much as 48 quads). The realization of the maximum potential however, is a highly complex problem and essentially involves converting the U.S. economy or at least a portion of it to a biomass based energy supply. The environmental, legal and social aspects of large scale biomass development need to be addressed in a comprehensive fashion.

The cost of biomass energy is projected to be less than or up to double the cost of present fossil fuels, but pilot operations are required to confirm these economic projections. An economic parameter requiring additional scrutiny is transportation cost, including its effect on production scale and the localization of markets for biomass fuel. This also leads to an evaluation of centralized vs. decentralized biomass production-consumption schemes.

An important question to be answered in large scale biomass production for energy is the effect of present and future competitive usage, primarily food production, on the availability of acreage. This should also involve analysis of the possible integrated systems for the production of food, fiber, energy and chemicals.

3. Fresh Water Farming

Fresh water farming has limited potential but promises higher yield per acre under optimal conditions (i.e., abundant nutrient supply and warm climate). While the conclusions for land farming are also applicable here, the cultivation, harvesting and processing of aquatic plants is less advanced than for land farming. As a result, economics are far less certain and require additional development.

4. Marine Farming

Marine farming promises to be the largest potential source of not only energy, but also of food. Realization of this goal will require not only basic research and development, but also coordination, management and integration of combined energy-food systems. The U.S. expertise in ocean farming is very limited and will require significant development at all levels.

Systems for energy farming in addition to the artificial floor modules for growing giant kelp should be investigated and developed. Sargassum, a free floating algae appears economical and technologically attractive and should be seriously evaluated.

SECTION VI

CHEMICALS FROM BIOMASS

A. BACKGROUND

The concept of a wood-based chemical industry reached its peak prior to World War II (27). In the emergency cases during the two World Wars, wherever the supplies of coal or petroleum were short, biomass was utilized: e.g., in World War I, Germany produced dynamite glycerine by sugar fermentation (28); in 1935 eleven countries consumed 576,000 tons of methanol and ethanol as a gasoline supplement (29); in 1945 the United Kingdom produced 500,000 tons of ethanol from potato fermentation (30), and during 1946-47 in Sweden there were 33 plants, producing 60,000 tons per year of ethanol from wood plus other products like methanol, acetone, acetic acid, naval stores, tall oil, ethylene, ethylene oxide, glycol, butanol, butyl acetate, wood tar and cellulosic polymers. Six of these plants are still active (31). In the United States, such emergency measures were exemplified in the formation of the "Chemurgic Council" of 1935 at the recommendation of Henry Ford, sugar rationing of 1940, and the production of 200,000 tons of butadiene from grain alcohol (32). The Emergency Rubber Project of 1942 produced 3 million tons of rubber (33).

After World War II low cost and highly versatile petroleum feed stocks rapidly captured the energy and chemicals market from other resources like coal and wood. In only three general areas, where lower cost and/or better quality were offered, were chemicals from biomass able to withstand and win the competition (see Table 4).

Table 4. Three Main Areas Where Chemicals From Biomass Have Not Lost to Petroleum

Polymers	By-products	Speciality Chemicals
Natural rubber Pulp Cellulose Chemical cellulose Cellulose esters Cellulose ethers Cotton still provides 50% of the worlds textiles versus 29% by synthetics (39)	From Pulp Mills: Dimethyl sulfoxide Naval Stores Tall oil Turpentine Lignin products Vanillin From Sugar Mills: Ethanol Acetone Butanol Fumeric Acid Others: Glycerol from animal fat and corncobs Furfural from corncobs	Drying oils Fatty acids Waxes Soaps Natural Dyes Sugars

Only Sweden and the U.S.S.R. have major, continued interests in utilizing biomass (e.g., in the U.S.S.R. approximately 15 industrial plants are based on acid hydrolysis of woods for use in yeast production (34)).

The prospects for utilizing biomass for the production of chemicals depends upon the economic determinants, among which two of the most important are the suitability of the alternative raw material feedstocks and their appropriate conversion processes. Historically, coal replaced wood as the major chemical feedstock but eventually lost to petroleum. Coal still remains a strong contender for use as the principal raw material feed-stock for chemical production, due to its high carbon content, chemical uniformity, well developed technology and dependability of the supply. Biomass, on the other hand, is highly dispersed, non-uniform, and suffers from lack of assured supply (crop failures).

It is important to point out the difficulty found with regard to estimating costs. This originates from the fact that very little operational data, if any, is available. Beside certain biased assumptions, other factors like geography, type of biomass, etc., further complicate the matter. For example, the assumption that the price of the wood feedstock declines as the production improves is questionable. In a market where the price of petroleum fuels increase, the price of other fuels will also increase. Thus, the price of wood fuel will be closely connected to other fuel prices. Another factor is the availability of wood, and the effect of transportation costs in limiting production scale.

The ability to provide a steady, long-term supply of wood exceeding one million tons per year for a given location seems questionable (35,36). With regard to multiproduct plants, it must be mentioned that although the economics improves, they have the serious disadvantage of not being adaptable to market demand fluctuation or to producing other chemicals when called for because of their fixed mode of production.

In the final analysis the cost of the conversion process determines whether or not chemicals from biomass will be economically feasible. Essentially the conversion processes involve the depolymerization of the lignocellulosic structure of the biomass, and it is here that the diversity of the chemical structure becomes a considerably complicating factor. For example, wood essentially consists of cellulose, hemicellulose and lignin. Whereas waste paper, grains and aquatic biomass are basically free of lignin, straw has a low lignin content and urban waste is a highly complicated substance. Therefore, a conversion method suitable for all types of biomass is not available. Still another factor is the competition between various biomass sources. For example, furfural can be obtained both from barley straw and from prehydrolysis of hardwood in a Kraft pulp mill. These considerations make rigorous economic analysis almost impossible.

Despite these problems and uncertainties, interest in biomass derived chemicals and fuels has increased dramatically (see Appendix A, Table A-3 for a list of current activities).

Due to world wide response to the oil crisis, other countries have also become involved: For example, Brazil is presently conducting a large ethanol from sugarcane project (37). Interest has also been developing in the production of rubber from Guayule and a whale oil substitute from Jojoba.

As noted, a variety of chemicals can be economically obtained either as by-products or speciality items, and will continue to be so in the future (Table 4). For example, fermentation derived ethanol in the United States has risen from 10 percent in 1975 to 30 percent of the total United States ethanol production in 1976. This has been achieved in the "integrated" grain milling plants where potable and industrial ethanol are produced along with other corn products (32).

B. ASSESSMENT OF ECONOMIC FEASIBILITY

The economic feasibility of chemicals from biomass depends on several factors, among them being the cost and supply of petrochemicals in the future, cost and supply of biomass and finally the size and cost of the conversion process. To estimate these parameters, the following methodology is commonly practiced:

(1) Identify the large market petrochemicals that are obtainable from biomass in good yields (see Table 5).

(2) Determine their future supply and demand as well as their petroleum and coal derived prices.

(3) Estimate the cost of producing them from suitable biomass via the best conversion process available. It is here where, due to future developments, most of the uncertainties originate.

(4) Compare the future prices to determine the time of feasibility.

(5) Weigh side effects of shifting from petroleum to biomass, such as socio-economical as well as environmental.

Two recent studies have addressed the economic feasibility of producing some of the large volume chemicals from wood. These results are summarized in Appendix B, Tables B-2 - B-7 and Figs. B-2 - B-6. It shows that ethanol production from corn is superior to that from wood (Tables B-3 and B-7) and methanol from coal is cheaper than from wood (Tables B-5 and B-6). Table 5 shows a list of important petrochemicals and their near-term future demand assessments.

On the basis of near-term unsatisfied demand, the production of ammonia and hydrogen from biomass are promising candidates and need closer examination. Ammonia (hence hydrogen) presents an interesting case; according to the Mitre Corp.(4), its production from wood is economical today and its future prices are about one half of those projected by Exxon (82) for coal derived ammonia. Presumably with a proper supply of wood or other suitable biomass one could manufacture hydrogen and ammonia at a currently competitive price. These projections obviously require substantiation but identify a potentially promising area of future investigation.

Table 5. Future Demand Assessment of Petrochemicals (Until the Turn of the Century) (38)

Chemical	Current Source	Current Production Tg/y	Demand Assessment
Methanol	Natural Gas	2.93	Saturated by future supply (if no gasohol)
Ammonia	Natural Gas	14.65	Unsatisfied
Hydrogen	Natural Gas	6.8	Unsatisfied
Ethylene	Natural Gas	11.17	Saturated (present supply 2X demands)
Ethanol	Ethylene	0.59	Saturated (if no gasohol)
Formaldehyde	Methanol	2.75 (37% wt. solution)	Saturated
Phenol	Benzene from coal and petroleum	1.08	Saturated
Acetic acid	Ethanol	1.17	Saturated

*Tg = Teragram (10^{12}g)/year

C. POTENTIAL ENERGY CONTRIBUTION

Today about 6-8 percent of our current petroleum usage is devoted to the production of chemicals. Of this amount, two-thirds is consumed as process heat and one-third (1.5 quads) actually ends up as petrochemicals. The production of ammonia alone accounts for the consumption of about 0.7 quads of oil and gas annually. The production of ammonia from biomass promises to give the single most important contribution in terms of total energy input. Technology for a wood-based ammonia production is available and favorable economics have been projected. The potential energy contribution of non-fuel chemicals from biomass is very small compared to that of the fuel chemicals such as ethanol, CH_4 and H_2. The energy contribution of these chemicals is expected to be limited by biomass production and conversion technology rather than by future market demand.

D. CHEMICAL VS. FUEL AND MATERIAL PRODUCTS

As already pointed out replacement of petroleum by chemicals from biomass results in an insignificant savings in petroleum. Direct use of biomass as fuel, however, has a far greater chance of being realized than its use as a chemical feedstock because it does not require extensive research and development and does not involve heavy capital investments. For example, the forest products industry has achieved 40-45 percent energy self sufficiency by burning its biomass residues. Realizing complete energy self sufficiency in this industry (36,39) would amount to liberation of 1.6 quads of fossil fuel which is equivalent to the petroleum consumed in petrochemicals production.

Another way in which biomass, especially wood, contributes to the nation's energy supply is its application as a structural material. Wood products are not energy intensive, compared to other materials like metals, and plastics. The equivalent of 0.9 tons of coal is required to produce a ton of paper in comparison with 9 tons for aluminum and 6 tons for plastics (36). The substitution of metals and plastics by wood products, where possible, appears desirable from an energy standpoint. Along this same line of argument, it must be pointed out that many petrochemicals eventually end up as polymeric products; hence, it seems logical to exploit the polymeric nature of wood constituents, especially cellulose and lignin, rather than trying to destroy it. A crucial need exists for better solvents for these polymers and improved methods of separation in the wood products industry to maintain a favorable economic position for these biomass derived polymers.

While the future of chemicals from biomass and biomass use as fuel are complicated issues, current economic, environmental and energy considerations are pushing the pulp and cellulose industries to take full advantage of these by-products and wastes. A good example here is furfural which is currently underutilized and is a potentially useful intermediate from which ethylene glycol, maleic anhydride, tetrahydrofuran, nylon 66, etc., can be obtained. It is along this kind of evolutionary path that the utilization of cellulose and lignin polymers will be expanded and many chemical by-products from other biomass sources will be marketed.

E. SOURCE OF FUNDING

Approximately $1.5 million is available from DOE for R&D in deriving chemicals from biomass, in addition to research sponsored in-house by the forest products industries and USDA. The ASRA directorate of NSF has designated $4.7 million for biological nitrogen fixation (ammonia production), conversion of ligno-cellulose to chemicals and rubber production from guayule.

F. CONCLUSIONS

Historically, chemicals from biomass have withstood and won the competition against the low-cost petroleum in three main areas: specialty items, by-products and polymer cellulose. With the rising costs of petroleum, biomass utilization will further expand. This is particularly true for forest product industries and others based on annual crops like sugar and corn. Progress will be made in the direction of solving their waste disposal problems while at the same time trying to recover valuable products.

A processing plant solely for the purpose of converting biomass to chemicals does not seem economical, especially when one considers the extensive research and development needed and the heavy capital investments necessary. A multi-product operation, although it appears more viable, suffers from a lack of flexibility to market demands, because it can only produce a specific group of chemicals in a fixed proportion. Only where vast supplies of biomass are locally available and petroleum and coal are expensive, will it be feasible to convert biomass to chemicals, i.e., a situation encountered in the next century.

Even if the production of chemicals from biomass were economical today, and all of the United States chemical demands were met by biomass feed stocks, the resultant oil and gas savings would be equivalent to 1.5 quads (feedstock only - not including fuel used in processing) which is comparable to the present contribution made by biomass as fuel. If only the forest products industry alone would utilize more of its wastes in order to become energy self-sufficient (now 40-45% self-sufficient), it would liberate enough oil (1.6 quads) with which all the 32 million tons of petrochemicals could be made. Thus, in this light, it makes sense to make the best use of the fuel value of biomass.

Since most petrochemicals end up as polymeric products, the most sensible utilization of ligno-cellulosic biomass would be the exploitation of the polymeric nature of its constituents, lignin and cellulose.

Finding an industrial cellulose solvent and discovering feasible methods of separating polymeric lignin from polymer cellulose are crucial research objectives in furthering the use of cellulose and lignin. Investigation on cellulose sources other than cotton and wood, like kenaf, bamboo, wheat straw, and other cellulose rich annual crops is also important.

Since structural materials like metals and plastics are energy intensive their substitution by wood and other biomass products that are far less energy consumptive is highly desirable.

Ammonia (hence hydrogen) accounts for about 1/2 of the consumption of natural gas supplies and is projected to be economically produced from biomass. The production of ammonia (H_2) is the most promising candidate for production of chemicals from biomass.

SECTION VII

THERMOCHEMICAL CONVERSION OF BIOMASS TO FUELS

A. BACKGROUND

Biomass will theoretically supply a significant portion of the nation's energy requirements; however, biomass is a widely dispersed fuel with a much lower heat quality than the petroleum based fuels to which the national economy is geared. Although some biomass is burned directly for heat production, the collection and conversion of biomass to more usable forms is highly desirable in order to achieve a broad based usage of biomass energy.

Thermochemical processing of organic material affords several advantages over biological conversion: 1) high flexibility makes it possible to produce various types of fuels; 2) less capital investment is required, and 3) medium heating value gases can be obtained especially where indirect heating is utilized. Some disadvantages of thermochemical systems are also apparent: 1) environmental impact is greater for thermochemical processes and 2) waste heat, gases and solids are present. Many types of thermochemical processes are under investigation for conversion of organic materials to various types of fuels. The energy conversion processes discussed in the following section include pyrolysis and partial oxidation, incineration, catalytic gasification, chemical reduction, hydrogasification and wet-air oxidation. A summary of current activities is found in Appendix A, Tables A-4 and A-5. These processes are briefly described below.

1. Pyrolysis and Partial Oxidation

a. Process Description. Considerable confusion exists over the meaning or definition of pyrolysis. Weinstein and Toro (40) state:

> "Pyrolysis or 'destructive distillation' is a process in which organic material is decomposed at elevated temperature in either an oxygen-free or low-oxygen atmosphere. Unlike incineration, which is inherently a highly exothermic combustion reaction with air, pyrolysis requires the application of heat, either indirectly or by partial oxidation or other reactions occurring in the pyrolysis reactor. Again unlike incineration, which produces primarily carbon dioxide and water, the products of pyrolysis are normally a complex mixture of primarily combustible gases, liquids and solid residues."

Other authors (41) define pyrolysis as thermal decomposition without complete combustion. A more rigorous definition of pyrolysis is an irreversible chemical transformation of material due to the agency of heat alone in the absence of oxygen (42).

For this report no attempt is made to separate partial oxidation processes from those that are truly pyrolytic. This is in consonance with most review articles on thermal conversion of materials for fuels.

The emergence of pyrolysis processes as a viable alternative to current methods of waste disposal indicates the versatility of the process. The proposed applications of pyrolysis to the disposal of widely differing wastes of organic origin (municipal, industrial, agricultural, etc.) demonstrate the technical simplicity of the process. The kinetics and transport phenomena of pyrolysis processes of organic wastes, however, are poorly understood at the present time. The lack of knowledge of the kinetics and transport processes makes it imperative for scale-up purposes to conduct pilot-plant studies of each new pyrolysis scheme designed for a specific waste. The kinetics and reaction mechanisms of pyrolysis of pure compounds have been extensively studied and documented. Pyrolysis of organic wastes and complex organic compounds (wood, cellulose, lignin, synthetic polymers, etc.), however, is a complex process consisting of several chemical and physical steps. The complexity of this process can best be appreciated when one finds widely different reaction rate constants and reaction mechanisms proposed for the pyrolysis of cellulose alone. In the case of organic wastes, which comprise numerous organic compounds of varying concentrations, it is all but impossible to predict the rate of reaction and product distribution. The chemical literature is abundant in the information on pyrolysis reactions of simple organic compounds. This will not be considered here. Instead, the pyrolysis of organic wastes and residues will be examined from the standpoint of bench or pilot-scale studies and commercial or large-scale demonstration projects.

The basic characteristics of various pyrolysis/partial oxidation reactor systems are tabulated in Appendix B, Table B-8. A summary of ongoing pyrolysis processes with regard to reactor types, product distribution, feed conditions and status of the work is presented in Table B-10.

b. Process Economics. The Advanced Technology - Mix Energy Systems Program (ATMES) Technology Evaluation of Solid Waste Pyrolysis (43) compares the technical and economical features of the various pyrolysis concepts which are considered commercial or close to being commercial. The findings of this comparison are summarized in Appendix B, Table B-10. The ATMES report states that pyrolysis is presently in the development stage and that the economics are not well defined.

It should be emphasized that the pyrolysis processes considered in the ATMES study are basically refuse disposal systems with credit taken for solids disposal.

Many economic assessments of fuel production by pyrolysis of wastes or grown biomass have been conducted. Most are based on minimal data from small pilot-scale or laboratory experiments, different capacities or scale of production, and different economic methods are frequently employed, therefore, comparative analysis is tenuous and care must be exercised in consideration of economic feasibility on the basis of these studies.

A recent study on SNG from Biomass (44) determined a cost range of \$0.15-\$4.45/10^6 Btu for SNG from urban solid waste with the price dependent on waste disposal credit. For a 3000 TPD municipal solid waste disposal facility, Del Bel, et al. (45) present a figure of \$3.37/10^6 Btu for pyrolysis. A NASA study (46) by the Lewis Research Center of systems for deriving liquid and gaseous fuels from waste or grown organics discloses that the major influence on the cost of fuel is the charge for the biomass feedstock, regardless of the conversion process used. For pyrolysis of slash pine at \$35.91 per metric ton, net cost was \$5.09/10^6 Btu. This compares with \$0.77/10^6 Btu for pyrolysis of waste material with credit taken for waste disposal.

2. Incineration

a. Process Description. Due to the solid waste problem and the energy potential of waste, engineers have concentrated on methods of extracting energy from wastes. The problem of space has long been a concern of European countries and they have turned to incineration as a solution. Thus, much of our technology is derived from their practice.

A major benefit of incineration is volume reduction. Up to 92 percent volume reduction and 80 percent weight reduction can be achieved in a typical incineration process (41). The technology has improved considerably such that the pre-1968 pollution problems have been largely eliminated.

Incineration systems can be divided into three major classifications:

(1) Direct incineration for steam generation in the boiler.

(2) Incineration with supplemental fuel for steam generation.

(3) Direct utilization of combustion gases for electrical power generation.

b. Process Economics. It can be summarized that refuse burning will be more costly than landfill even with credits for steam and metals. However, where landfills become prohibitive as they have been in Europe for years and are becoming so in metropolitan areas such as New York, incineration is necessary. If a market for the steam produced is available a very good relationship can exist between waste disposal and energy production. Up to now little coordinated effort has been made in this direction. For example, the Chicago Northwest incinerator condenses most of the steam produced due to a lack of market. The use of materials other than waste for incineration for steam generation has also been initiated. The Green Mountain facility in Vermont for the burning of wood chips with oil is in the planning stage. Agricultural wastes would have use in a system of this type if the wastes could be gathered and concentrated in an economic manner.

3. Hydrogasification of Cellulosic Wastes

a. Process Description. The hydrogasification process was originally developed for production of synthetic natural gas from coal. In this process, much of the methane is formed by the direct reaction of hydrogen with carbon in the organic feed. The reaction is done at 800°C and 1,000 psi. Pressure increases the yield of methane. The char from the reactor is utilized in hydrogen production. The raw gas from the hydrogasifier is scrubbed to remove particulate matter and acidic impurities and then flows to the methanator where excess hydrogen reacts with carbon monoxide to form additional methane.

b. Process Economics. The economic evaluation of this process in comparison to other processing schemes for MSW utilization is shown in Table 6 (45).

Table 6. Estimated Cost of Various MSW Processing Facilities

(3000 TPD)

Process	Direct Firing	Pyrolysis to Gas	Hydro-gasification	Liquefaction
Installed Cost ($ MM)	33	80.5	107.6	111.6
Annual Cost ($1000/yr)	5610	20,490	8,872	13,097
Annual Cost ($/MM Btu)	0.72	3.37	1.25	1.70

4. Steam and Electricity from Wet Oxidation Process

a. Process Description. Wet oxidation process, which is alternately called wet air oxidation (WAO) or wet combustion process is based on the reaction of oxygen with organic compounds either suspended or dissolved in water. This reaction proceeds at reasonable rates at elevated temperatures (150-350°C), while pressure is maintained at levels high enough to prevent excessive evaporation, generally 300-3,000 psi. Wet oxidation takes place by a family of related oxidative and hydrolytic reactions, which lead to a range of intermediate products and finally to carbon dioxide and water.

The main advantage of wet oxidation process is in its high efficiency regardless of moisture content of the fuel. The second advantage is in the variety of low quality fuels which can be accepted (sewage sludge, peat, pulp liquor, etc.) and the low level of gaseous pollutants which are emitted into the atmosphere. The main disadvantage is its high initial capital and operating cost, even though it is claimed by its proponents that it would be on a par with fluidized bed combustion units or even lower than a stoker furnace with scrubbers. Another disadvantage of the process when utilized for steam production is the limitation on the steam pressure which can be obtained (100-800 psig, more realistically 100-250 psig). About 100 commercial wet oxidation units are already in operation around the world, primarily for recovery of energy and chemicals in paper pulping operations and also for sewage sludge disposal. The process seems to be promising for energy recovery from peat deposits and some waste materials.

5. Oil from Cellulose - PERC Process

a. Process Description. The PERC process,(47) developed by the Pittsburgh Energy Research Center (PERC), converts cellulosic wastes (wood, paper, straw, etc.) into bitumen or oil by reaction with carbon monoxide and water. Alkaline metal or alkaline earth metal carbonates serve as catalysts. The reaction is carried out at 250-400°C and a pressure of 1,500-3,500 psig. Production yield of oil is 45-60% of dry weight of wood at 100% conversion. This variability in yield stems from variable oxygen content in the final product. This oxygen content also lowers the heating value, so that the BTU content of this oil is not higher than about 80% of the BTU content of a petroleum oil.

b. Process Economics. The projected economics of this process is summarized in Table 7 (47).

Table 7. Summarized Economics for Conversion of Urban and Wood Wastes

Urban Wastes	1500 tons/day
Wood Wastes	1500 tons/day
Total Wastes Utilized	3000 tons/day
Waste-to-Oil Production	2082 tons/day
Waste for Synthesis Gas and Heat	918 tons/day
Oil Production Rate	3618 barrels/day
Operating Costs	$9.48/ton waste

Assumed value of oil ($/bbl)	Break-even disposal charge ($/ton of wastes)
6.60	2.24
7.00	1.04
8.00	-0.17
9.00	-1.37
10.00	-2.58

The process has been selected for further development by a Fuels from Biomass Branch of DOE and a 3 ton/day pilot plant was recently built in Albany, Oregon (48). Numerous problems were encountered during the initial operation. A major problem was pressure containments in the stirred tank reactor. As the result of these observations, the equipment is now being redesigned so that the reactor will utilize static mixers for internal heat transfer and no mechanical equipment will be utilized internally.

6. Catalytic Gasification

a. Process Description. The use of catalysts in gasification schemes is largely an empirical process. In one refuse using plan, Na_2CO_3 is used to improve the yield of water gas in a rotary kiln steam or hydrogasification process (49).

Research at Battelle Laboratories in Columbus, Ohio has led to a catalytic pretreatment process to bring about enhancement of methane. The project summary from the Biomass Systems Research of the Department of Energy outlines the objective of the system (50).

Research objectives of the Battelle process are to:

- Determine the increase in the overall gasification rate brought about by the pretreatment step;
- Establish the optimum range of conditions for biomass gasification; and
- Prepare a technoeconomic assessment of the process for the production of a methane-rich gas from forest residues.

The homogeneity and abundance of waste wood cellulose should be a contributing factor to the success of this research. The impact of this process is not the process itself but the fact that there are possible catalytic methods to enhance energy recovery from wastes when transforming the raw materials into such items as gas or possibly liquid fuel. Such research has not been carried out to any great extent in the biomass area.

B. POTENTIAL ENERGY CONTRIBUTION

The energy potential for thermochemical processing of biomass depends for the most part on the availability of the biomass. Reliable estimates are available on the total tonnage of organic wastes such as manure, urban refuse, logging and wood manufacturing residues, agricultural crop and food wastes, industrial wastes, and municipal sewage solids for a total amount of about 1,000 million tons per year. Large quantities of these material are not available for processing as a result of their widely dispersed locations and the expense associated with collection. Furthermore, considerable biomass is too high in moisture content for economic thermochemical energy recovery; biological processing is more suitable for these materials.

The quantities of relatively dry materials such as wood and wood wastes are vast. These materials are suitable for thermochemical processing and are currently being utilized primarily by the lumbering, pulp and paper industry to make them about 40 percent energy self-sufficient. If and when the energy plantation concept comes to fruition, then the energy contribution from the plant mass will be immense. The potential energy contribution is open to conjecture, but some reasonable estimates have been made (see Biomass Source section, this report).

Recovery of energy from biomass is complex; however, technologies are presently available in various stages of development for thermochemical processing and energy recovery. Most of the conversion schemes are 60-70% efficient in energy recovery except for direct combustion which is higher in efficiency but limited in product flexibility. In summary, the potential for fuels from biomass is significant and thermochemical processing will play a major role in energy recovery.

The final criterion for process selection will be based solely on economics; i.e., the process of choice will be the one yielding the cheapest fuel.

C. SOURCES OF FUNDING

Primary funding agencies for research on thermochemical conversion of biomass for fuels include the following:

(1) Department of Energy
Fuels from Biomass Systems Branch
Division of Solar Energy

(2) Environmental Protection Agency
Fuels Technology Branch

(3) Department of Energy
Urban Waste Technology Branch

D. CONCLUSIONS

(1) The problem of inaccuracy of available information in the fuels from biomass field has created difficulties in economic assessments over the past few years. Data from small-scale pilot plants have been used for projections for commercial facilities; these data, of course, yield questionable results. Large-scale demonstration plants are now on line and meaningful data are now becoming available.

(2) Pyrolysis systems afford distinct advantages over most biomass conversion systems including incineration in that a variety of fuels is possible. Liquid, solid, and medium BTU gaseous fuels can be produced by pyrolysis for on site use or for transportation.

(3) Incineration on site affords the best energy recovery system, i.e., conversion is high. Corrosion problems are severe as a result of deposits and fly ash.

(4) Fuels from agricultural wastes, manures, and other high moisture materials are best derived from biological conversion unless highly efficient drying systems can be used in conjunction with thermochemical processing.

(5) Thermochemical conversion of biomass has added desirability when environmental credits can also be obtained. An example of such a situation is the utilization of chaparral for energy and/or chemical feedstocks. An elimination of disastrous forest fires and the enhancement of recreational areas are desirable aspects of chaparral management.

(6) The utilization of waste materials on site as an energy source or for production of materials for use in the chemical process or for sale appears beneficial. An example of upgrading of a waste to a high value product would be the conversion to activated carbon for subsequent use in oil purification or waste water treatment.

(7) The need for mobile conversion plants is obvious. The EPA has recently issued an RFP for construction and testing of a 200 ton/day mobile system in California.

(8) Conversion of biomass to transportable fuels (major thrust area of DOE) or to specific chemicals such as ethylene appears to have potential. The Navy's work at China Lake for pyrolysis to gasoline and the ethylene production work at Arizona are yielding interesting results.

(9) The conversion scheme which shows the lowest cost will be the most desirable regardless of fuel quality.

SECTION VIII

BIOLOGICAL CONVERSION OF BIOMASS TO FUELS AND CHEMICALS

A. BACKGROUND

Biological methods for converting biomass to more versatile fuels principally have an advantage over physical processes where the biomass material has a high water content. Biological reactions are also intrinsically much more specific than physical chemical methods, but characteristically involve slow reaction rates and dilute solutions. For the purpose of this study these processes are subdivided into anaerobic, aerobic and enzyme processes.

1. Anaerobic Processes

Anaerobic fermentation is defined as the biological degradation of organic materials in the absence of elemental oxygen. The microorganisms involved derive the energy they require for reproduction and growth by oxidizing chemically bound carbon to carbon dioxide. The required oxygen for this process is supplied by chemically bound oxygen. Since simultaneous chemical reduction of other carbon compounds is also involved, a major portion of the energy of the starting material is conserved in the end products of the fermentation. A variety of products which are suitable for fuels and chemicals can be obtained as end products of anaerobic fermentation. These include: hydrogen, methane, ethanol, acetone, isopropanol, butanol and 2,3-butanediol (see Appendix A, Table A-6 for a list of current activities). From an energy standpoint, the major emphasis is placed on methane and ethanol, since these are versatile fuels which have readily available markets (see section on Chemicals from Biomass). These two are discussed below.

a. Methane Production. The anaerobic production of methane occurs in two steps. In the acid forming phase complex biomass materials are degraded to H_2, CO_2 and low molecular weight compounds, i.e., acetate, formate, propionate and ethanol, by a wide variety of heterotrophic microorganisms. In the second step (methane forming phase), methane is produced through the reduction of CO_2 with H_2 and from the disproportionation of simple organic acids to CO_2 and methane (51). Methane production is accomplished by species of the genus Methanobacter which are fastidious, strict anaerobes. While the biochemistry and microbiology of Methanobacter have not been adequately studied, the process of anaerobic digestion (for methane) has long been used in sewage treatment. Process studies have concentrated on empirical investigations of digestion conditions, digestibility of feed materials and yields of methane. A major emphasis has been placed on the digestion of feed lot wastes due to the availability of substantial volumes of manures and environmental requirements of the feed lot industry. The Indian government is successfully promoting small scale digesters in rural India for the production of methane and fertilizer from animal manures (1). The high protein residue from the digester has also been successfully used as an animal feed supplement (1). Methanogenesis is proposed as the primary conversion process for producing energy from ocean biomass (44), and will be used in the GRI-GE ocean energy farming program. Present studies are also being carried out to analyze the economics of production, collection, distribution and pre-treatment associated with various organic wastes. Appendix A, Table A-6 contains a list of the major organizations, personnel and funding for research in anaerobic digestion. The ease of separation of product from the aqueous solution is a major advantage of methane as the final fuel product. Unfortunately the methane forming phase is quite slow and sensitive to pH and oxygen. Economic viability for methane production depends largely on increasing the rate of methane formation to reduce process retention times.

b. Ethanol. The biological production of ethanol is an ancient and well studied process and accounts for a minor fraction of the current U.S. industrial ethanol production (see Chemicals from Biomass). Under conditions of O_2 limitation naturally occuring strains of yeasts and some bacteria ferment simple sugars to ethanol and CO_2. When adequate oxygen is available the strains metabolize ethanol to CO_2 and water. Commercial production is normally accomplished by yeast strains with hydrolyzed starch as an energy source. The principle problem of ethanol production from biomass is the hydrolysis of biomass to simple sugars. While this is readily accomplished with starch, cellulose, the principal component of most biomass, is much more resistant to processing. The utilization of cellulose appears to be a key factor in the large scale economic production of ethanol from biomass in the U.S. Brazil is presently pursuing an aggressive program for fermenting sugar cane juice to ethanol for use as a motor fuel. This is currently economical in Brazil due to a high gasoline tax so that the ethanol produced at $1.40 per gallon is economically competitive (34,37), and due to a favorable climate for sugar cane.

2. Aerobic Processes

Aerobic processes, by definition, include all microbial processes performed in the presence of O_2. In the presence of oxygen most organisms obtain energy for growth and replication by degrading fixed carbon to CO_2 and water, thus destroying the fuel value of the material. Limited aerobic digestion of fixed carbon can be achieved with appropriate microbial strains as in the classical production of vinegar (acetic acid) (53) and citric acid (54). A mutant yeast which is unable to utilize ethanol for growth was recently reported (55). Ethanol production by this strain under aerobic conditions was reported to be five times faster than that of the usual anaerobic process, but no yield data are available. This is likely due to an increased growth rate since about ten times more energy is available to the organisms through the aerobic pathway than through the anaerobic route (56). Tailoring special strains for the limited aerobic degradation of carbon materials to fuels to provide improved processes for fuel production appears to be an attractive area of research.

Aerobic processes can also be used to obtain biosynthetic products such as amino acids, vitamins, fats, oils, proteins, carbohydrates, etc. Since this route is relatively inefficient, it is likely to be limited to the production of important chemicals, whereas the more energy efficient anaerobic degradation will successfully compete for the production of fuels. There is some room for producing fuels by modified aerobic processes. Successful application in this area will depend largely on the economics of production compared to that from fossil fuel sources. A crucial factor is the selection and development of strains which direct large amounts of energy into the desired product. The fact that naturally occuring strains can produce up to 50% of the total cell mass as a single storage product is encouraging (57). Photosynthetic microorganisms provide a potentially promising approach to biosynthetic products. Instead of producing a cellulose based biomass for conversion to fuels and chemicals, algae or higher plants might be modified to economically produce chemicals directly--H_2(biophotolysis), glycerol, fats, oils. These would then be extracted for use either as fuel or chemicals. A current precedent is the production of natural rubber from Hevea. A glycerol based biomass system using algae has been proposed (55) and digestion of algal biomass to methane has received considerable study (58).

Aerobic digestion of sewage sludge is also popular. This conserves energy by reducing the volume of sewage solids before transportation to landfill sites.

3. Enzyme Processes

Enzymes are high molecular weight (10,000 - 500,000 daltons), highly specific catalysts which mediate nearly all of the chemical reactions in biological systems. The principle distinction between enzyme processing and other biological methods is that enzyme processing involves either purified enzymes or crude preparations in the absence of living cells. Since enzymes are the catalysts of biological systems, enzyme processes share the advantages of other biological processes, i.e., specificity and operation in aqueous solutions at ambient conditions. Where the required task is simple the use of enzymes offers greater specificity and energy efficiency than whole cell processing particularly where the enzyme is stable and readily recovered for reuse. In many cases enzymes perform reactions with virtually no competing side reactions and normally possess absolute stereospecificity for products and reactants. The specificity of enzymes is very important in food processing, hence, the primary application of enzyme technology is in that industry. All current processes employ degradative enzymes, the most important of which are proteases and amylases. The present commerical market for all enzymes is around $50 million dollars per year. The use of enzymes in chemical synthesis depends primarily on developing methods for economical regeneration of the enzyme cofactors ATP and NADH. The status of enzyme technology was recently reviewed (59). Appendix A, Table A-8 lists current research in the area.

The application of enzymes to energy production is primarily limited to the use of cellulase systems for the degradation of cellulose to glucose. The glucose product is a highly versatile fermentation feedstock and can be used in the production of most fuels and chemicals. Current work at the U.S. Army laboratory in Natick, Mass., is concerned with genetic improvement of Trichoderma viride for cellulase production and subsequent commercialization for ethanol production (60). The Natick group is currently running a pre-pilot scale demonstration which processes 1000 pounds of newsprint or urban waste per month. Their immediate goal is a 4000 pounds per month operation (59,60).

Acid hydrolysis of cellulose is the competing process for cellulose degradation. While acid hydrolysis is currently cheaper than enzymatic degradation, improvements in enzyme production, stabilization and recovery may yield a competitive enzyme process for the degradation of newsprint. The Natick group now claims that ethanol can be produced for $0.89/gallon (60) although this has yet to be proven on a larger scale.

Cellulose degradation is complicated by the fact that cellulose sources vary in degradability, depending on the crystalinity and the amount of associated lignin. Cellulose also contains considerable amounts of hemicellulose (pentose polymer). While hemicellulose is more easily degraded than cellulose, the enzymes responsible are only beginning to be characterized. The pentose sugars resulting from hemicellulose hydrolysis are not utilized by yeast for ethanol production so suitable utilization schemes will require development. Enzymatic degradation of lignin is another energy related application but the present results are not encouraging. Lignin contains a highly variable structure and is difficult to degrade biologically.

B. POTENTIAL ENERGY CONTRIBUTION

The potential of biological conversion processes for energy production is very difficult to quantitate. Important factors in assessing such potential are the production of suitable biomass feedstocks, the economics of the biological process in question and the competing alternative processes. The ultimate potential of land and fresh water farming appears to be in the range of 16-48 quads/year (see Biomass Sources), while ocean farming could be considerably greater, depending on the development of appropriate technologies. Thermochemical processes are expected to predominate the conversion market with wood and other poorly biodegradable, low moisture biomass sources. Biological processes therefore are likely to be quite limited in the land farming area unless the biological technologies are substantially improved. The retention of nitrogen fertilizer value or protein production by anaerobic digestion, may provide sufficient advantage to dictate widespread use of anaerobic digestion in rural settings. If ocean energy farming technology becomes reality, anaerobic digestion for methane is likely to be the major contributing process in U.S. energy production from biomass sources. Aerobic processes are likely to be limited to the chemical market (see Chemicals from Biomass) unless good technologies for aerobic ethanol production are developed and ethanol finds a major use in motor fuel. The production of methane and ethanol currently appears to account for the majority of the potential for biological conversions of biomass materials. The potential of enzyme processes appears limited except as they apply to the production of methane and ethanol.

C. SOURCES OF FUNDING

The Fuels from Biomass Program of DOE is the primary source of funding for the production of fuels by biological processes. The DOE program is highly application oriented and prefers pilot scale or immediate application projects. The NSF (ASRA directorate) funds research on biological processes for the production of chemicals from ligno-cellulose materials. The Gas Research Institute funds research on anaerobic digestion in conjunction with their current ocean energy farms program.

D. CONCLUSIONS

1. Anaerobic Processes

Anaerobic fermentations for the production of methane and ethanol will be important processes in the field of energy from biomass. Both of these processes appear to be on the margins of economic viability. Reasonable improvements in these technologies could provide a substantial benefit to the production of energy from biomass. Key areas of interest in technological development are:

a) Increasing the rate of methane production either by process engineering or by microbial genetics.

b) Improving separation technology in order to economically extract useful degradation intermediates, i.e., ethanol, acetone, 2,3-butanediol, acetate, both for chemicals and chemical intermediates and for energy production.

c) Increasing the biodegradeability of cellulose containing biomass either by pretreatment technologies or through improved biological processes. In addition, developing degradation and utilization methodologies for hemicellulose containing biomass.

d) Developing rapid standard techniques for measurement of biodegradability of biomass materials.

e) Developing anaerobic digestion process models which would include data relating fermentation kinetics to fermentation temperatures for specific substrates, techniques for storage and preparation of each substrate, and the evaluation of potential health and environmental problems associated with process residues.

f) Determining appropriate usage for the high protein sludge from anaerobic fermentors as animal feed and developing acceptable processes of extracting protein or other dietary supplements, i.e., vitamins, from anaerobic digester sludge.

2. Aerobic Processes

Aerobic processes for processing biomass will likely be limited to the production of foods and chemicals while anaerobic processes will predominate in fuel production. Genetically tailoring specific strains for fuel production in aerobic environments appears promising.

Specific attention should be devoted to photosynthetic organisms (algae and higher plants) for the direct production of important fuel and chemical substances.

3. Enzyme Processes

Most current enzyme based technology is only related to energy indirectly. Since these catalysts operate under mild conditions and require little energy consumption a small measure of energy conservation is achieved.

Enzyme processes in energy production will be limited to degradation reactions in the near future. The use of enzyme systems in synthesis will require economical methods of cofactor regeneration. The most important energy related enzymes are those involved with the degradation of cellulose and hemicellulose. Fruitful research areas include: 1) Enzyme hydrolysis of agricultural wastes, 2) development of enzymatic degradation of hemi-cellulose and 3) developing schemes for the conversion of hemicellulose degradation products to fuels and chemicals.

SECTION IX

BASIC BIOCONVERSION SCIENCES

A. BACKGROUND

While the biological sciences have made enormous progress over the past several decades, the areas described below have not kept pace with other disciplines due to the low availability of funding. Investigations in these areas are now highly relevant to the production of energy through bioconversion and basic investigations may well provide technology breakthroughs which will directly benefit the national economy. While only the major areas of photosynthesis, N_2 fixation and biophotolysis are considered below, a greater variety of important areas are likely to emerge as the field develops.

1. Biological Photosynthesis

Since the assimilation of all chemical energy and organic carbon into a plant is mediated by the reactions of photosynthesis, the ultimate potential productivity of any plant will depend upon the efficiency and capacity of the photosynthetic machinery. The overall process of photosynthesis can be considered to be composed of two partial processes. First, the capture of solar energy in the form of ATP and NADPH (eq. 1.), and second, the reduction of carbon dioxide to carbohydrate (eq. 2.) using ATP and NADPH.

$$H_2O + ADP + NADP^+ + Pi \xrightarrow{\text{Light}} 1/2\ O_2 + ATP + NADPH + H^+ \qquad (1)$$

$$H^+ + 6CO_2 + 18ATP + 12NADPH \longrightarrow \text{hexose} + 18\ ADP + 18Pi + 12NADP^+ \qquad (2)$$

The maximum theoretical efficiency of the conversion of solar energy to glucose has been calculated as 12.3% of the incident solar energy (61).

Presently, agronomic crops have a short-term percent conversion efficiency ranging from 1.4 percent for rice grain to 4.2 percent for napier grass (62). The discrepancy in efficiency can be ascribed to a variety of factors such as, temperature, nutritional deficiencies, physical stress or predation by other organisms. These limitations can usually be mitigated by presently available techniques. Perhaps a more fundamental limitation is the loss of previously fixed carbon by reaction with O_2 in the light dependent process known as photorespiration.

The initial reaction involves fixing molecular oxygen via RUDP carboxylase to yield phosphoglycollic acid and 3-phosphoglyceric acid. Several reaction schemes have been proposed to account for the CO_2 release from glycollate. It is generally accepted that glycollate is oxidized to glyoxylate in the peroxisomes and subsequently transaminated to glycine. Glycine is then transported to the mitochondria and converted to serine and CO_2. An alternate pathway for CO_2 liberation is a direct decarboxylation of glyoxylate to formate by a non-enzymatic reaction with H_2O_2. Although there is sufficient catalase in the peroxisomes to destroy 80 percent or more of the H_2O_2 generated, de novo H_2O_2 synthesis could occur in the mitochondria by superoxide dismutases which catalyzes the breakdown of O_2^- to O_2, and H_2O_2 (63). There is overwhelming evidence that photorespiration in many species occurs at rates of at least 50 percent of CO_2 uptake (64).

A basic strategy for improving plant yields concerns the genetic (or possibly chemical) modification of carbon assimilation to reduce photorespiration. Oliver and Zelitch have been able to double net photosynthetic CO_2 fixation of tobacco leaf disks by glyoxylate treatment (65), indicating that photorespiration can be metabolically regulated. A second approach to increasing photosynthetic efficiency is based on the fact that, in addition to the universal C_3 metabolism of green plants, some plants such as maize, sorghum and sugar cane, assimilate carbon by a C_4 pathway. In these plants CO_2 is fixed by the carboxylation of phosphoenolpyruvate (PEP) to form C_4 organic acids. The distinguishing feature of these plants is that they photorespire at a very low rate and are therefore more efficient in the capture of the solar flux. One favored hypothesis is a casual relationship between the "Kranz" anatomy of C_4 plants and the low levels of photorespiration (66). In this model CO_2 is fixed into C_4 acids in mesophyll cells. The C_4 acids are then transported to the bundle sheath cells surrounding the vascular tissue where the C_3 metabolism operates. The CO_2 liberated during glycollate metabolism (photorespiration) is not allowed to escape into the atmosphere due to the unique leaf anatomy of the C_4 plants, but is re-utilized in the C_3 carbon assimilation cycle. However, there is strong evidence that the peculiar "Kranz" anatomy is neither a necessary requirement not its presence a guarantee of C_4 metabolism (67,68). The basis of this more efficient process and its application to crop improvement therefore, remains to be resolved.

A third approach to plant improvement is to develop drought resistant species for growth in arid regions. Succulent plants which are highly drought resistant possess a carbon assimilation mode (CAM = crassulacean acid metabolism) similar to C_4 fixation. These plants conserve water (69) by keeping the stoma closed during the day. Stoma are opened during the night and carbon is fixed into C_4 acids. During the day when light energy is available the C_4 acids are decarboxylated to CO_2 which is fixed into carbohydrate through the normal C_3 metabolic pathway (70-72). This is a less efficient process that daytime photosynthesis and adequate watering will eliminate the CAM mode in succulents (73). This peculiar metabolism however, allows survival under extreme conditions of drought. This mode is also thought to be responsible for salt tolerance (74) which is another important avenue of crop improvement.

Several methodologies are crucial to all areas of development. In addition to the standard techniques of plant breeding and selection, the ability to manipulate the genetics of plant cells _in vitro_ is an extremely powerful technique. The mechanisms for genetic change _in vitro_ include standard mutagenesis and transformation as well as the developing techniques of cell fusion and recombinant DNA transfer. Successful intrageneric (71) hybridizations through cell fusion have been reported (75,76), but a detailed knowledge of the mechanisms involved is lacking and limits the application of the technique. Recombinant techniques are beginning to succeed in prokaryotes. Important problems in recombinant technology are isolation of the required gene in pure form and achieving expression and appropriate regulation in the host. The successful application of recombinant technology is considered a long term goal.

In all _in vitro_ methods, effective selection procedures and successful plant regeneration are crucial to developing new plants. Sufficient precedent exists for regeneration (tobbacco and carrot) to expect success but only a few species have been regenerated successfully and considerable activity will be required to develop the field to a useful stage.

2. _Biological Nitrogen Fixation_

Nitrogen fixation (Eq. 3) is part of the biological nitrogen cycle

$$N_2 + 6e^- + 6H^+ + nATP \longrightarrow 2NH_3 + nADP + nPi \qquad (3)$$

which includes nitrification (the oxidation of ammonia) and denitrification (the reduction of nitrate back to N_2 gas). The current interest in biological nitrogen fixation stems from the fact that U.S. high productivity agriculture is extremely dependent upon the application of fixed nitrogen fertilizers and that current supplies of commercially fixed nitrogen are primarily derived from natural gas in the United States. Hardy (77) has adequately presented the case for the importance of nitrogen fertilizer and concluded that nitrogen fertilization is the single most important non-biological factor in increasing cereal grain production. In this regard, the importance of biological nitrogen fixation transcends the concerns of the current energy crisis in relation to food production. The heavy application of commercial fixed nitrogen also leads to water pollution by runoff. Developing appropriate biological systems therefore may also provide an environmental advantage. Finally, full advantage of biological N_2 fixation is probably required in the production of energy from biomass to obtain maximum energy output/energy input ratios by avoiding the requirement for fertilization with fixed nitrogen.

The ability to fix atmospheric nitrogen appears to be restricted to a relatively few prokaryotes. Within the prokaryotes, a wide variety of organisms exist including anaerobic and aerobic heterotrophs, photosynthetic bacteria and blue green algae. Similar diversity exists in the systems which fix nitrogen. These range from the simple free-living nitrogen-fixing microorganisms which fix nitrogen only for their own use to very complex systems such as legumes in which symbiotic bacteria are fed by the plant in specialized structures (nodules) and the bacteria in turn fix nitrogen for use by the plant.

The application of biological systems for nitrogen fixation spans the spectrum from growing alfalfa to recombinant DNA technology. Simple approaches such as crop rotation of legumes and grains and green manuring with legumes or other nitrogen fixing systems have been employed for many years to enhance agriculture productivity. While these practices lost a considerable amount of their importance in the U.S. with the advent of cheap nitrogen fertilizer, current influences may well revitalize these older methods. The current tendency, however, is to place the emphasis on developing new more promising methods of enhancing biological nitrogen fixation. This interest has largely emerged from the research community, and the field is largely research oriented. With the exception of DuPont which has had an active research group in this area for years, major involvement by the industrial sector is not apparent.

Current activities in biological nitrogen fixation are broadly distributed. Since this area has been recently reviewed, the reader is referred to the literature for additional information (48). A list of the primary people involved in the U.S. can be found in Appendix A, Table A-9. At present considerable attention is being devoted to developing a basic understanding of the processes involved in biological nitrogen fixation including: the structure and function of the nitrogenase enzyme, the physiology of nitrogen fixation in both free-living and symbiotic microorganisms, the genetics and control of the process, and the basis of symbiotic nitrogen fixation (i.e., host recognition, nitrogen assimilation, etc.). Considerable attention has also focused on more applied aspects such as developing improved strains of legumes and rhizobia and the related activity of identifying new naturally occurring symbioses of potential agronomic importance. Production of fixed nitrogen by free-living nitrogen fixers or non-legume systems is being investigated as is their current contribution to agriculture. Blue green algae and Azolla in conjunction with rice culture are two of the more important systems in this regard (78-79). Perhaps the most sensational aspect of the field is developing strains of cereal grains which fix nitrogen either by direct transfer of the nif (nitrogen fixation) genes to higher plants or developing new symbioses through cell fusion or selection.

3. Biophotolysis

Biophotolysis is defined as the splitting of water to yield oxygen and hydrogen using photon energy. Basically two approaches exist in this area: 1) production of hydrogen by living systems (in vivo) and 2) separation and stabilization of components from living systems for H_2 production (in vitro). The basic reaction scheme is depicted in Figure 1.

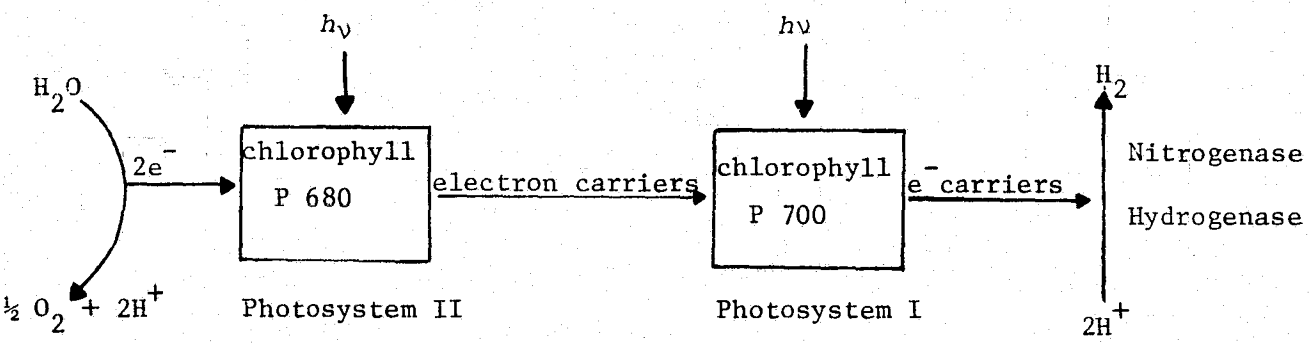

Figure 1. Basic Reaction Scheme for Biophotolysis

After the oxidation of H_2O, electrons are excited in chlorophyll P680 by light. These electrons are passed through a number of electron carriers and another photoexcitation by chlorophyll P700 provides sufficient energy that the electrons can be passed to either the hydrogenase or the nitrogenase enzymes for the production of hydrogen. The hydrogenase enzyme catalyzes the reversible equilibration of hydrogen with H_3O^+ (eq. 4).

$$2H_2O + H_2 \longleftrightarrow 2H_3O^+ + 2e^- \qquad (4)$$

Nitrogenase normally functions to provide fixed nitrogen for the organism (eq. 3). The production of H_2 is a side reaction of N_2 fixation and in the absence of N_2 and presence of H^+, available electrons are used to produce H_2. Nitrogenase is less efficient than hydrogenase since it uses additional energy in the form of ATP. Nitrogenase, however, is essentially irreversible and may in the final analysis be more suitable for hydrogen production by *in vivo* systems.

Biophotolysis is theoretically attractive as a direct route to fuel without involving the biomass and subsequent conversion steps. However, a number of serious problems exist, the solutions to which will require major technical breakthroughs. Probably the major problem is the O_2 sensitivity of the hydrogen producing enzymes, hydrogenase and nitrogenase. Since algal systems possess O_2 protection of nitrogenase, H_2 production via nitrogenase is likely the whole cell candidate of choice for further improvement of rates and yields. A recent report of hydrogen production by a marine algae appears the most promising accomplishment to date (80). *In vitro* systems, in addition to being oxygen sensitive, are relatively unstable under currently employed conditions. Significant breakthroughs in stabilization of the required enzymes and separation of the O_2 and H_2 generating activities are required to consider <u>in vitro</u> biophotolysis a viable option for energy production. While progress is being made in this direction (81) the development of practical systems is not imminent. Nonbiological systems for H_2O photolysis are also being explored and may in some cases provide a solution to the above problems.

Biophotolysis has no present commercial application due to the low rates of H_2 production in present systems. The majority of current investigators are listed in Appendix A, Table A-10.

B. POTENTIAL CONTRIBUTION TO U.S. ENERGY PRODUCTION

1. Photosynthesis Research

The current production and eventual potential of biomass energy was treated under biomass sources. While the effect of basic research on biomass yield and therefore energy production cannot be accurately estimated, if only a fraction of the success achieved in food production by the green revolution could be achieved in biomass production, a considerable contribution would be realized. Based on estimated potential (see Biomass sources) a modest 20% increase in biomass yields could correspond to an additional 8 quads of energy per year for optimistic projections in land farming. Whether this is achievable is unknown since considerable research effort is required to assess the possibilities for genetic improvements of biomass crops for BTU production.

2. Biological Nitrogen Fixation

The present levels of global biological nitrogen fixation, are estimated at 175×10^6 metric tons which is about 3.5 times the current industrial production. Biological nitrogen fixation accounts for nearly 70 percent of the total nitrogen fixed by all processes including industrial, lightning, etc. Of the total biological fixation, 89 x 10^6 metric tons occur in agricultural settings primarily by legumes (78). This illustrates the current importance of biological nitrogen fixation to our agricultural economy. The current U.S. production of synthetic nitrogen (around 16.5 x 10^6 tons per year) is accomplished by the Haber Process which is primarily based on natural gas. The production of a ton of ammonia consumes 42 x 10^6 BTU/ton (65). Assuming the production of 16 x 10^6 tons per year, ammonia production accounts for nearly 1 percent of the United States total energy usage. Development of appropriate biological systems to eliminate the need for nitrogen fertilizer could therefore, supply up to 1% of current energy usage, and benefit biomass production.

3. Biophotolysis

Adequate data for estimating the contribution of biophotolysis does not exist. Hydrogen is a fundamental material in the energy picture and presumably could find a place as the major energy intermediate of the economy provided appropriate economics and technology are achieved.

C. SOURCES OF FUNDING

Public funding in the United States for research in biological nitrogen fixation and photosynthesis is primarily handled by the National Science Foundation and the Department of Agriculture. While some money for basic studies in these areas is available through the Directorate for Biological, Behavorial and Social Sciences of NSF, the Applied Sciences and Research Application Directorate (ASRA), has designated $4.7 million for the bioconversion of lignocellulose to chemicals, biological nitrogen fixation and production of rubber from Guayule. U.S.D.A. funds nitrogen fixation research in-house and through grants to universities. A considerable increase occurred in FY 78 by the implementation of a competitive grants program which distributed 10 million dollars for basic research in the areas of plant stress, biological nitrogen fixation, increasing photosynthetic efficiency and genetic engineering for crop improvement. The FY 79 program will be funded at FY 78 levels.

Biophotolysis is currently funded at less than $1 million primarily from NSF and DOE. SERI has an active developing biophotolysis program.

D. CONCLUSIONS

Plant sciences in the U.S. have been traditionally neglected. Many very fruitful areas for basic investigation exist and will likely receive increased attention as their relevance to energy production is recognized. Areas which are currently being considered are:

1. Biological Photosynthesis

A considerable gap exists between the theoretical photosynthetic efficiency of green plants and that which is achieved under even reasonably ideal condition. Providing a basic understanding of photorespiration and the various photosynthetic mechanisms of carbon fixation (C_3, C_4 and CAM) is necessary to gain insight and perspective into the problem of increasing the photosynthetic efficiency of higher plants.

The genetic manipulation and selection of higher plants *in vitro* is an extremely powerful technique for crop improvement both in food and energy crops. Methodologies which require substantial development to make *in vitro* techniques practical include: 1) mutagenesis in higher plants, 2) effective selection procedures for desirable phenotypes, 3) propagation of whole plants from laboratory clones, 4) cell fusion techniques for intergeneric DNA transfers and 5) recombinant DNA technologies in higher plants.

2. Biological Nitrogen Fixation

Biological nitrogen fixation is currently an important process since it generates 3.5 times as much nitrogen as industrial production on a global scale. Eliminating the U.S. requirement for commercial fertilizers would conserve about 1.0% of our current energy usage. In addition, developing practical techniques of biological fertilization are very important to the production of energy from biomass to maintain favorable economics and energy input/output ratios. An area of primary importance is that of developing new nitrogen fixing plant systems either by direct genetic manipulation of the plant or by developing symbiotic associations between plants and bacteria. Nitrogen fixing cereals and nitrogen fixing biomass crops appear to have the major potential. Probably of equal importance is the genetic improvement of existing symbioses both for food and biomass production. Important fundamental problems in relation to these areas are: 1) elucidation of the mechanism of symbiosis, including host recognition, nitrogen assimilation and control; 2) understanding the control and function of nitrogen fixation in both symbiotic and free living systems. 3) devising methods for the transfer of the _nif_ genes to higher plants and 4) devising screening procedures for improving important naturally occuring symbioses.

3. Biophotolysis

Biophotolysis provides an attractive route from photon energy to usable fuels without going through the biomass and subsequent conversion steps. At present, however, no practical systems have been developed for hydrogen or electricity production and major technical breakthroughs appear required for the development of practical systems. The primary problems are: 1) increasing the rate and yield of H_2 production of _in vitro_ systems, 2) stabilizing _in vitro_ systems and

3) protection of components from O_2 inactivation and separation of reducing and oxidizing products.

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APPENDIX A

CURRENT ACTIVITIES IN BIOCONVERSION

The following tables contain appended material from each of the areas discussed in the report. The following list allows the reader to cross reference the tables to a particular area:

Biomass Sources	Tables A-1 and A-2
Chemicals from Biomass	Table A-3
Thermochemical Processes	Tables A-4 and A-5
Biological Processes	Tables A-6 through A-8
Basic Biological Sciences	Tables A-9 and A-10

Table A-1. Biomass Sources - Organizations and Personnel

Project Title	Principal Investigators	Organization	Amount Awarded
Sugar Cane Spacing Study	J. E. Irvine	Agric. Res. Svc. U. S. Sugar Cane Field Laboratory Hanum, La.	$40K
Preliminary Evaluation of a New Process for Separation of Components of Sugar Cane, Sweet Sorghum and Other Plant Stalks	J. Atchison	J. E. Atchison Consultants, Inc. New York, New York	$9.8K
Energy Farming Concepts Based on Sugar Cane, Sweet Sorghum and Sugar Beets	E. S. Lipinsky	Babelle-Columbus Laboratories, Columbus, Ohio	$446K
Planting of Sugar Cane in Florida Row Spacing and Experiment	D. L. Myhre	University of Florida Belle Glade, Florida	$4K
Establishment of Populus Energy Plantation	D. Dawson	U. S. Forest Service North Central Forest Experiment Station St. Paul, Minnesota	$243K
Fuel Plantation Research	J. Stubbs	U. S. Forest Service Southeast Forest Experiment Station, Ashenville, N.C.	$113K

Table A-1. Biomass Sources - Organizations and Personnel (Continued)

Project Title	Principal Investigators	Organization	Amount Awarded
Construction and Field Trials of a Prototype Forest Land Residue Machine (Mobile Hog) to harvest fuel from forest residues or from Energy Plantation	P. Koch	U. S. Forest Service The Southern Forest Experiment Station Pineville, La.	$200K
Biomass Production of Short Rotation Coppice Forestry	K. Steinbeck G. Brown	University of Georgia School of Forest Resources, Athens, Ga.	$259K
The Photosynthesis Energy Factory	Szego	Intertechnology Corp.	$226K
Hydrocarbons and Energy from Plants	M. Calvin	Lawrence Berkeley Laboratories University of California Berkeley, California	$37K
Harvesting and Transportation of Sugar Cane	J. A. Polack	Louisiana State University Dept. of Chem. Engineering Baton Rouge, La.	$11K
To demonstrate the feasibility of a Fuel Plantation as a new source of energy	E. Mariani	Norelco, Inc. Alexandria, Virginia	$73K
System Study of Fuels from Grains and Grasses	W. R. Benson	Midwest Research Inst. Kansas City, Mo.	$201K

Table A-1. Biomass Sources - Organizations and Personnel (Continued)

Project Title	Principal Investigators	Organization	Amount Awarded
Structuring Silviculture Farm Development	R. Inman	Mitre Corp., Metrek Div. McLean, Virginia	$148K
Production of Sugar Cane and Tropical Grasses as a Renewable Energy Source	A. G. Alexander	University of Puerto Rico Rio Piedras, Puerto Rico	$214K

Table A-2. Research on Algae as a Biomass Source

Project Title	Principal Investigators	Organization	Funding Level
An Integrated System for Conversion of Solar Energy Using Waste Grown Filamentous Blue-Green Algae Biomass	W. J. Oswald	University of California Sanitary Eng. Res. Lab. College of Engineering Richmond, Calif.	$216K
Algae Concentration by Ultrafiltration	H. P. Gregor R. Cardenas	Columbia University New York, N.Y.	$88K
Cost Analysis of Algae Biomass Systems	D. Wise	Dynatech R/D Company, Cambridge, Mass.	$ Unknown
Cultivation of Microscopic Marine Algae and Freshwater Aquatic Weeds[a]	J. H. Ryther	Woods Hole Oceanographic Institution Woods Hole, Mass.	$206K
The Photosynthesis Energy Factory[b]	Szego	Intertechnology Corp. Warrenton, Virginia	$226K

[a] This project is also listed under Marine Farming.

[b] This project is also listed under Land Farming.

Table A-3. Chemicals from Biomass (Current Activities)

Activity	Personnel	Organization	Funding Source
Production of ammonia from cattle manure via moving bed gasification (expl)*	W. J. Hoffman	Texas Tech. Lubbock, Tex.	DOE ERDA Private (R. Ward)
Production of natural rubber, and fuel oil from Guayule (expl)	M. Calvin	Lawrence Livermore Laboratory, U. C. Berkeley	DOE R. Ward
Production of pure silicon from rice hull via combustion	---	U. C. Berkeley Chemistry Dept.	---
Production of furfural and glucan from hardwoods via strong sulfuric acid hydrolysis (expl)	S. F. Harris	Forest Products Lab., Madison, Wisconsin	USDA
Bacterial delignification waste wood for the purpose of animal feedstock	C. A. Reddy	Microbiology Dept. Mich. State Univ. East Lansing, Mich.	NSF
	A. Baker	Forest Products Labs, Madison, Wisconsin	USDA
Production of chemicals by biotransformation of lignin present in Kraft liquor (expl)	S. W. Drew	Chemic. Eng. Dept. Virginia Polytech & State Univ. Blacksburg, VA.	NSF
Utilization of lignin present in pulp spent liquors in textile fibers (expl)	N. E. Franks	American Enka N. C.	In House
Production of mannose chemicals from wood	F. W. Herrick	ITT, Rayonier Shelton, Wash.	In House
Search for commercial cellulose solvent (expl)	A. F. Turbak	ITT, Rayonier Whippany, N. J.	In House

*expl = experimental

Table A-3. Chemicals from Biomass (Current Activities) (Continued)

Activity	Personnel	Organization	Funding Source
Sugars and Acids from oxidative hydrolysis of cellulose (expl)	D. L. Brink	U. C. Berkeley	NSF
Oleoresins and Hydrocarbons from pinewood (expl)	D. R. Roberts	Southeastern Forest Expl. Stn. Olutsee, Fla.	DOE
Conversion of Wood and pulp residues to alcohol, furfural and phenols (expl)	J. Saeman	Forest Products Labs, Madison, Wisconsin	USDA
Acetic Acid Production from marine algae (expl)	D. L. Wise	Dynatech R/D Co. Cambridge, MA	DOE
Degradation of cellulosic biomass to chemicals (expl)	D. I. C. Wang	MIT Cambridge, MA	DOE
Petrochemicals from fermentation of biomass (expl)	H. Bungay	Rensseler Polytech. Troy, New York	DOE
Utilization of Lignin in pulp wastes for production of pharmaceuticals (expl)	J. Nakano	Dept. of Forest Products. Univ. Tokyo, Japan	---
Enzymatic Hydrolysis of cellulosic wastes to glucose (pilot)	L. A. Spano	U.S. Army Natick Dev. Center Natick, Ma.	DOD
Production of Alcohol by fermentation of pulp wastes (demonstration)	---	Gulf Oil Corp	In-House
Study Enzymatic Hydrolysis of cellulose and subsequent glucose fermentation to alcohol	C. R. Wilke	Chem. Eng. Dept. U. C. Berkeley	DOE

Table A-3. Chemicals from Biomass (Current Activities) (Continued)

Activity	Personnel	Organization	Funding Source
Enhanced Acid Hydrolysis (combined mechanical and v-radiation) of waste paper	W. Brenner	New York Univ. Dept. of Applied Sciences New York, N.Y.	EPA
Fundamental Study of Kinetics of Acid and Enzyme Hydrolysis of Cellulose	G. T. Tsao	Chem. Eng. Dept. Purdue Univ. W. Laffayette, Indiana	DOE
Acid Hydrolysis of Concentrated Slurries of Cellulosic Biomass (expl)	H. Grethlein	Dartmouth College N. H.	DOE
Bioconversion of Plant Biomass to Ethanol (expl)	M. T. Su	General Electric Schenectady, N.Y.	DOE
Biological Production of Organic Solvents from Cellulosic Wastes	E. K. Pye	Univ. of Penn. Phil., PA.	DOE
Production of Glycerol from Algae Grown in Highly Saline Water	---	Weizman Inst. of Koor Foods, Ltd. Israel	---

Table A-4. Thermochemical Processes[a]

Waste Feed	Primary Energy Products	Conversion Process	Feed Conditions			Status (tpd)			Location	Operator
			Raw	Size Red	Sepn.	Res.[b]	Pilot	Comm.[c]		
Refuse	Steam, metals aggregate	Pyrolysis		X				1000	Baltimore, MD	Monsanto and City
Refuse	Lowgrade liquid fuel, metals, glass	Flash pyrolysis		X	X		200		San Diego, CA	Occidental Petroleum
Refuse	Low Btu gas, aggregate	Pyrolysis	X				75		Erie County, NY	Andco-Torrax (Carborundum Co)
Refuse	Low-Btu gas	Pyrolysis		X			2		Richland, WN	Batelle Pacific N-W Labs
Refuse	Low-Btu gas	Pyrolysis		X			120	1500	Queens, NY	Devco Mgt. Inc.
Refuse	Low-Btu gas	Pyrolysis					75		Riverside, Inc. CA	Pyrolysis System Inc.
Refuse	Low-Btu gas	Two-bed Pyrolysis		X	X	X			Morgantown, W. Va.	U. of W. Virginia
Refuse	Low-Btu gas	Pyrolysis	X				120		East Grandby, CT	Union R/D Corp.

Table A-4. Thermochemical Processes[a] (Continued)

Waste Feed	Primary Energy Products	Conversion Process	Feed Conditions			Status (tpd)			Location	Operator
			Raw	Size Red	Sepn.	Res.[b]	Pilot	Comm.[c]		
Industrial Scrap	Low-Btu gas, methanol char chemicals	Pyrolysis	X				400		Iron Mountain, MI	Ford Motor Co. (in 1920's-1930's)
Crop and Forest Residue	Low-Btu gas	Pyrolysis		X		X			U.C. Davis	U.C. Davis, John Deere Corp.
Sludge and RDF	Med-low Btu gas	Pyrolysis	X				144		Belmont, CA	BSP/Envirot.
Sewage Sludge	Char. steam	Pyrolysis	X			X			Belle Meade, NJ	Nichols Energy and Rsch Corp.
Dry Manure	Med Btu gas	Pyrolysis	X			X			Claremont, CA	Garrett Energy Research and Engineering
Sewage Sludge	Activated charcoal, med Btu gas	Pyrolysis	X				2		Orange Cty, CA	County Sanitation District and JPL
Tires	Oil, carbon black	Pyrolysis		X	X		15		Los Angeles, CA	Tosco Corp., Goodyear Tire and Rubber

Table A-4. Thermochemical Processes[a] (Continued)

Waste Feed	Primary Energy Products	Conversion Process	Feed Conditions			Status (tpd)			Location	Operator
			Raw	Size Red	Sepn.	Res.[b]	Pilot	Comm.[b]		
Scrap Rubber	Oil, carbon black	Pyrolysis	X	X		X			U. of Tennessee	U. of Tennessee
Refuse	Oil, gas, char	Pyrolysis	X				2		Cambridge, MA	Energy Resource Co. (ERCO)
Sugar Cane Bo gasse	Steam	Incineration		X				X	Hawaiian Islands	Utility Companies and Sugar Companies
Refuse	Steam, metals	Incineration		X	X			600	Hamilton, Ontario	City
Refuse	Fiber, steam	Pyrolysis			X wet pulp		40		Franklin, OH	Black Clauson's fiberdaim.
Refuse	Electricity from combustion gases	Incineration		X	X		70		Menlo Park, CA	Combustion Power Company
Refuse	Steam	Incineration	X					240	Braintree, MA	City
Refuse	Steam, metals	Incineration			X			1600	Chicago, IL	City

Table A-4. Thermochemical Processes[a] (Continued)

Waste Feed	Primary Energy Products	Conversion Process	Feed Conditions			Status (tpd)			Location	Operator
			Raw	Size Red	Sepn.	Res.[b]	Pilot	Comm.[c]		
Refuse	Steam, metals	Incineration			X			360	Harrisburg, PA	City
Refuse	Steam	Incineration	X					720	Nashville, TN	Nashville Thermal Transfer Corp.
Refuse	Steam, ferrous metals, aggregate	Incineration			X			1200	Saugus, MA	Refuse-Energy Systems Co.
Forest and Logging Residue, Whole Trees	Steam	Incineration	X					4000 KW	Milton, VT	Green Mountain Power Co.
Refuse	Low Btu gas, ferrous metals, aggregate	Partial oxidation	X		X	X			South Charleston, W. VA.	Union Carbide
Refuse	SNG, metals, aggregate	Partial oxidation and cat-methanation				X			Lowell, MA	SCA and Union Carbide

Table A-4. Thermochemical Processes[a] (Continued)

Waste Feed	Primary Energy Products	Conversion Process	Feed Conditions			Status (tpd)			Location	Operator
			Raw	Size Red	Sepn.	Res.[b]	Pilot	Comm.[c]		
Manure	SNG	Hydrogasification				X			Pittsburgh, PA	Bureau of Mines
Cellulosic Residues	Med grade fuel oil	PERC process $CO-H_2O$ Reaction	X			X			Albany, OR	FFB Branch of DOE

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[a] This list is only a sampling of the various processes.

[b] Research

[c] Commercial

Table A-5. EPA Funded Projectes in Thermochemical Processes (Partial List)

Investigating Unit	Expenditures	Objective	Biomass	End Product
1. Midwest Research Institute 425 Volker Boulevard Kansas City, MO 64110	15,000	Study of St. Louis Meremac Supplemental Fired Plant	Refuse	Steam - Electricity
2. Maryland Environmental Services State of Maryland 60 West St. Annapolis, Maryland 21401	200,000	Study of W-firing waste with coal in a cement kiln	Refuse	Cement
3. Systems Technology Corp. 245 N. Valley Road Xenia, Ohio 45345	119,000	Demonstrate use of drdf* as fuel supplement in stoker equipped boilers.	Refuse	Fuel for incinerators
4. Dow Chemical Co. Texas Division Freeport, Texas 77541	21,000	Making drdf	Refuse	Fuel for incinerators
5. R. Nelson, City of Tacoma, Washington 989 Broadway Tacoma, Washington (206) 593-4240	168,000	Refuse fired combustor feasibility study	Refuse	Steam
6. Monsanto Research Corp. Dayton Laboratory 1515 Nichols Road Dayton, Ohio 45407	25,000	Multi-waste Gasification Studies	Refuse	Research

*drdf = densified refuse-derived fuel

Table A-6. Anaerobic Digestion Research - Organizations and Personnel

Sponsor	Duration	Investigator	Expenditures $	Objective	Biomass	End Product
Texas State Govt.	2/74 - 5/74	Gloyna, E.F./Malina, J.F., Univ. of Texas College of Eng. Austin	5,000	Evaluate advances in recovering usable energy from municipal waste water	Municipal waste water	Methane recovery conceptual design for optimizing energy
National Science Foundation	7/64 - 6/75	Boersma, L. Oregon St. University, Dept. of Soil Sci., Corvallis, Or. 97331	Not Avail.	Development of an integrated production system in which resources are recycled	Animal Waste	Methane and High Protein Animal food. Improved energy utilization
Rockefeller Foundation	10/71 - 10/73	Chynoweth, D.P., Univ. of Michigan, Dept. of Environ. and Indust.		Conversion of fatty acids to methane	Urban and Indus. waste	Methane
Univ. of Mass./ Dynatech Corp.	6/73 - 7/76	Lindsey, E.E./ Short, W.L., Univ. of Mass., Dept. of Chem. Eng., Amherst, MA 01002	5,000	To obtain rate for the methane formation step	Municipal solid waste	Methane
National Science Foundation	6/74 - 5/76	McCarty, P.L. Stanford Univ. Dept. of Civil Eng., Stanford, CA 94305	48,000	Evaluate the efficacy of various heat treatments in increasing anaerobic biodegradability	Urban Agric. Waste	Methane

Table A-6. Anaerobic Digestion Research - Organizations and Personnel (Continued)

Sponsor	Duration	Investigator	Expenditures $	Objective	Biomass	End Product
Citizen Gas & Coke Utility	4/72 - 7/73	Klass, D., Institute of Gas Technology, Chicago, Ill. 60616	85,000	Biogasification of waste products to produce marketable products such as metals, glass, pipeline or low BTU gas	Municipal sludge & refuse, agricultural & industrial wastes	Methane
National Science Foundation, Div. of Adv. Energy Res. & Technol. & Dynatech Corp.	6/73 - 12/74	Wise, D.L., Dynatech Corp., Chemical Eng. Dept., Cambridge, MA 02139	469,000	Anaerobic digestion of cellulose to produce fuel gas	Municipal solid waste	Methane Gas
New England Regional Commission & University	7/73 - 7/75	Hassan, A./Rowe, R. University of Maine Dept. of Agricultural Eng. Orono, ME 04473	98,000	Investigate the use of organic wastes for the production of methane gas and protein feeds	Poultry manure	Methane & Protein Feed
Kansas State Govt., Dept. of Health & Environment	6/74 - 6/75	McKinney, R. University of Kansas Center for Research Inc. Lawrence, KS 60045	5,000	Evaluate existing anaerobic digestion units in Kansas (gas production)	Municipal waste plant and animal by-products	Methane Gas

Table A-6. Anaerobic Digestion Research - Organizations and Personnel (Continued)

Sponsor	Duration	Investigator	Expenditures $	Objective	Biomass	End Product
Encotech/ Univ. of Hawaii Agricultural Exp. Station	7/74 - 7/79	Ross, R./Koshi, J. H. University of Hawaii - Hawaii Agri. Exp. Station, Dept. of Animal Sci. Honolulu, Hawaii 96821	32,000	Define an animal waste recycling system	Animal waste and plant materials	Methane Sludge fertilizer High Protein Feed
Pennsylvania State Gov. Dept. of Agriculture	2/74 - 1/77	Persson, S.P.E. Pennsylvania State Univ., Dept. of Agric. Eng. Univ. Park, PA 16802	89,000	To find which structural and mechanical components, of the newly built anaerobic digester, are best suited with regards to cost, operation and safety.	Dairy herd manure and other farm by-products	Methane
U.S. Dept. of Agric. Clemson Univ.	7/72 - 7/75	Barth, C.L./Hill, D.T. Clemson University Dept. of Agric. Eng. Clemson, SC 29631	44,000	To evaluate prototype digester relative to amount and quality of gas produced as a function of loading and detention rate	Swine	Methane/Capture inorganic Nitrogen

Table A-6. Anaerobic Digestion Research - Organizations and Personnel (Continued)

Sponsor	Duration	Investigator	Expenditures $	Objective	Biomass	End Product
Southern California Edison	74-78	Univ. of Calif. Los Angeles/Southern California Edison Co. Rosemead, CA 91770	193,000	Determine the optical organic materials for methane production	Synthetic fuels	Methane and hydrogen
National Science Foundation	6/73 - 6/74	Cooney, C.L. Massachusetts Institute of Technology - Dept. of Nutrition and Food Sci. Cambridge, MA 02139	22,000	Conversion of cellulosic solid waste to fuel gas using thermophilic anaerobic digestion	Domestic cellulosic waste	Methane
National Science Foundation Div. of Adv. Energy Res. and Technology	6/74 - 5/75	Speece, R.E. Drexel University Graduate School Philadelphia, PA 19140	75,500	Evaluate feasibility of methane production through aerobic fermentation of selected soluble organic industrial wastewater	Industrial waste water	Methane
U.S. Dept. of Agric., Cooperative State Research Service	12/72 - 6/75	University of Wisconsin Madison, Dept. of Bacteriology Madison, WI 53706	17,530	Conversion of organic wastes into methane by thermophilic bacterial association	Agricultural waste	Methane

Table A-6. Anaerobic Digestion Research - Organizations and Personnel (Continued)

Sponsor	Duration	Investigator	Expenditures $	Objective	Biomass	End Product
National Science Foundation, Div. of Adv. Technology Applications (Energy Research & Development Adm.)	6/73 - 6/74	Zandi, I. University of Pennsylvania Dept. of Chem. Eng. Phila., PA 19104	97,500	Conversion of solar energy to fuel gas by anaerobic digestion of organic material derived from photo-syntehtic processes. To examine process dynamics in methane production by bacterial action	Organic wastes and harvested organic matter	Methane
National Science Foundation, RANN/ University of California - Richmond	5/73 - 10/75	Aswald, W.J., Golueke, C.G. University of Calif. Richmond, Sanitary Eng. Res. Lab Richmond, CA 94804	63,000	Conversion of solar energy via algal-bacterial systems to methane	Algae growing on wastes	Methane
National Science Foundation, RANN	6/74 - 6/75	McCarty, P.L. Stanford University Menlo Park, CA 9402	36,200	Evaluate the efficacy of various heat treatment procedures in converting refractory organic materials of biodegradable substances	Urban organic	Increase biodegradability of urban organic wastes

Table A-6. Anaerobic Digestion Research - Organizations and Personnel (Continued)

Sponsor	Duration	Investigator	Expenditures $	Objective	Biomass	End Product
National Science Foundation, RANN/Cornell University	4/74 - 9/75	Jewell, J.W. Cornell Univ. Dept. of Agric. Eng. Ithaca, NY 14853	110,000	Evaluate overall feasibility of using anaerobic digestion of agricultural wastes to provide an energy source for agricultural operations	Agricultural organic waste	Methane & Pollution control

Table A-7. Aerobic Digestion Research - Organizations and Personnel

Individuals	Organization	Area of Expertise
Shuler, M. L.	Cornell University Ithaca, N. Y.	Chicken manure to chicken feed: A recycling of agric. nutrients
Hegg, R. A. Rakness, K. L.	Environmental Protection Agency Denver, Colorado 2793	Design considerations for aerobic digesters
Gyger, R. F. Doerflein, E. L.	Union Carbide Corporation Tonawanda, N. Y.	Use of pure oxygen with conventional air systems for petrochemical wastewater treatment
Benedict, A. H.	Howard Edde, Inc. Bellevue, Wash.	Effects of shock temperature on biological systems
Lake, H. W.	General Electric Co. Schenectady, N. Y.	Bioconversion of plant biomass to ethanol
Wilke, C. R.	California University, Berkeley Lawrence Berkeley Laboratory	Production of sugars and ethanol based on enzymatic hydrolysis of cellulose
Scheller, W. A.	Nebraska University Lincoln Dept of Chemical Engineering	Fuels (ethanol) from biomass

Table A-8. Enzyme Research - Organizations and Personnel

Sponsor	Duration	Investigator(s)	Expenditures $	Objectives	Biomass	Product
(1) Department of Energy (DOE)	12/67 - 12/77	T. M. Su General Electric R&D Ctr. P.O. Box 43 Bldg. 37, Rm. 207 Schenectady, N.Y. 12301	171,000	An integrated all biological conversion process	Cellulose	Ethanol
(2) DOE	10/76 - 10/77	C. R. Wilke Lawrence Berkeley Lab. University of California Berkeley, California 94720	190,000	Pilot plant studies on raw materials & operations; assessment of enzyme processes for cellulose, celloboise, lignen. Basic research	Cellulose lignin	Glucose to Ethanol, etc.
(3) DOE	12/76 - 11/77	Daniel I. C. Wang Dept. Nutr. and Food Science Mass. Inst. Techn. Cambridge, Mass. 02139	235,000	Use of Clostridium strains for cellulase production. Producing sugars for fermentation feedstocks	Cellulose	Butanol, CH_4, H_2, Acetic Acid
(4) DOE	9/76 - 9/77	E. Kendall Pye College Eng & Appl. Sciences University of Penn. Philadelphia, PA 19174	283,000	Use of Thermoactinomyles for cellulases to give sugars for fermentation feedstocks	Cellulose	Glucose

Table A-8. Enzyme Research - Organizations and Personnel (Continued)

Sponsor	Duration	Investigator(s)	Expenditures $	Objectives	Biomass	Product
(5) DOE	10/76 - 9/77	D. E. Eveleigh Rutgers University New Brunswick, N.J. 08903	35,900	Production higher yield mutants of *Trichoderma viride*	Cellulase	Basic Research
(6) Swedish Natural Science Research Council Private Foundations	N/A	LER Berghem, L.G. Pettersson, U.B Axio-Fredriksson Biokemiska Institutunen Uppsala University Box 531, S-75151 Uppsala, Sweden	N/A	Mechanisms of Enzymatic Cellulose Degradation.	Cellulose	Basic Research
(7) Private Foundations	N/A	Karl-Erik Eriksson Swedish Forest Products Research Labs. Chem.Dept.Box 5604 Stockholm, Sweden S-11486	N/A	Cellulase, Lignase Enzyme studies	Cellulose Lignin	Basic Research

Sources: References 50, 59, and literature searches of government funding agencies' documentation files.

Table A-9. Nitrogen Fixation Research - Organizations and Personnel

Organization	Personnel	Location
ARC - Unit of Nitrogen Fixation	John Postgate, Director	Sussex, England
C. F. Kettering Research Laboratory	M. Lamborg G. Peters W. D. Bauer D. Kuester	Yellow Springs, Ohio
University of Wisconsin	R. H. Burris W. Orme-Johnson W. J. Brill	Madison, Wisconsin
University of California	R. C. Valentine Don Phillips Bill Rains	Davis, California
Boyce Thompson Institute	A. A. App, Program Director of Cell Physiology	Yonkers, New York
Purdue University	L. E. Mortenson	Layfayette, Indiana
U.S.D.A.	N. C. Sloger D. Weber	Beltsville, Maryland
U.S.D.A.	J. W. Newton	Peoria, Illinois
Oregon State University	H. E. Evans	Corvallis, Oregon
Dupont	Ralph Hardy, Director of Research	Wilmington, Delaware
Harvard University	F. Ausubel	Cambridge, Mass.
M.I.T.	E. R. Signer	Cambridge, Mass.
North Carolina State University	G. Elkan	North Carolina
University of Dundee	W. D. P. Stewart	Dundee, Scotland
John Innes Institute	J. Berringer	Norwich, England

Table A-10. Biophotolysis Research — Organizations and Personnel

Individual	Institute	Funding Source
L. L. Kramptz	Case Western Reserve Microbiol. Dept. Cleveland, Ohio	Ethyl Corp.
T. S. Stuart	Dept. Pollution Control Tallahassee, Fla.	NSF
R. M. Pearlstein	Oak Ridge National Laboratory Biological Div. Oak Ridge, Tennessee	NSF (RANN)
K. J. Monty	University of Tennessee Biochemical Department	NSF (RANN)
R. K. Togasaki	Indiana University Dept. of Plant Sciences Bloomington, Indiana	NSF (RANN)
M. Mitsui	University of Miami School of Marine and Atm. Sci. Miami, Florida	NSF
D. King K. L. Erbes	Brandeis University Inst. Photobiol.	NSF
E. Greenbaum	Rockefeller University New York City, N. Y.	NSF
T. Yage	Shizuoka University Chemical Dept. Shizuoka, Japan	--
N. I. Bishop	Oregon State University Dept. of Botany and Plant Biol.	NSF
L. W. Jones	University of Tennessee Dept. of Botany Knoxville, Tennessee	NSF
A. I. Krasna	Columbus University College of Physicians New York City, N. Y.	--
A. H. Pelofsky	Booz Allen & Hamilton Inc. Florham Park, New Jersey	DOE

Table A-10. Biophotolysis Research – Organizations and Personnel (Continued)

Individual	Institute	Funding Source
W.J. Oswald	University of California Richmond, California	DOE
A. Ghosh	Exxon Research & Eng. Co. Linden, New Jersey	DOE

APPENDIX B

SUPPORTING DATA

Biomass Sources	Tables B-1 and B-2 Figure B-1
Chemicals from Biomass	Tables B-3 to B-7 Figures B-2 to B-6
Thermochemical Conversion of Biomass to Fuels	Tables B-8 to B-10

Table B-1. Estimates of Land Suitable and Potentially Available for Plantations, by State (Millions of Acres)(11)

State	Land Inventory Classification						Totals	State	Land Inventory Classification						Totals
	1	2	3	4	6	7			1	2	3	4	6	7	
Alabama	0.01	0.44	0.48	1.83	0.70	0.05	3.51	New Jersey	-	-	0.01	0.10	0.03	-	0.14
Arkansas	0.07	0.40	1.14	1.48	1.26	0.22	4.57	New York	0.01	0.19	0.53	1.86	0.94	0.04	3.56
Delaware	-	-	-	0.01	0.01	-	0.02	N. Carolina	-	0.08	0.14	1.26	0.54	0.15	2.18
Florida	-	0.20	1.90	5.91	0.16	-	8.17	Ohio	0.04	0.19	0.17	1.48	1.11	0.11	3.10
Georgia	0.02	0.38	0.62	1.34	0.48	0.01	2.95	Oklahoma	0.06	0.56	0.64	4.82	6.88	0.10	13.06
Illinois	0.10	0.28	0.17	1.95	1.31	0.12	3.93	Pennsylvania	0.01	0.12	0.15	1.74	0.78	0.07	2.87
Indiana	0.07	0.23	0.12	1.52	0.72	0.17	2.83	S. Carolina	-	0.15	0.17	0.89	0.18	0.40	1.79
Iowa	0.06	0.19	0.24	2.35	1.21	0.38	4.33	S. Dakota	-	0.03	-	0.80	0.95	-	2.05
Kansas	0.09	0.14	0.05	4.00	6.05	0.07	10.40	Tennessee	0.06	0.10	0.18	1.78	1.78	0.21	4.11
Kentucky	0.04	0.09	0.21	1.60	2.11	0.24	4.29	Texas	0.30	2.28	3.95	12.10	23.37	0.63	42.63
Louisiana	0.05	1.42	3.06	1.59	0.87	-	6.99	Vermont	-	0.01	0.01	0.30	0.03	0.01	0.36
Maine	-	0.02	0.02	0.19	0.14	-	0.37	Virginia	-	0.17	0.22	1.34	1.07	0.28	3.08
Maryland	-	0.05	0.03	0.30	0.20	0.02	0.60	West Virginia	-	0.02	0.05	0.50	0.76	0.32	1.65
Michigan	-	0.15	0.28	1.27	0.38	0.04	2.12	Wisconsin	0.01	0.50	0.42	3.05	1.18	0.15	5.31
Minnesota	-	0.50	0.45	3.24	1.04	0.14	5.37								
Mississippi	0.02	1.19	1.01	2.97	1.59	0.78	7.56								
Missouri	0.13	0.43	0.89	5.00	3.18	0.40	10.03	TOTALS	1.15	10.84	17.38	71.94	69.07	5.65	176.03
Nebraska	-	0.06	0.04	3.25	7.89	0.54	11.78								

TABLE B-2 (4)
LAND POTENTIALLY SUITABLE FOR BIOMASS FARMS
BY USDA FARM PRODUCTION REGION (4)

Millions of acres* (Percent of total)

REGION	SCENARIO 1[1]	%	SCENARIO 2[2]	%	SCENARIO 3[3]	%	SCENARIO 4[4]	%	WETLANDS[5]	%	USFS A[6]	%	USFS B[7]	%
Pacific	3.5	4	5.6	2	7.2	2	9.6	2	0.9	1	8.3	69	14.2	47
Northern Plains	1.3	2	6.5	2	9.1	3	21.6	4	0.6	1	0.0	0	0.0	0
Southern Plains	10.3	13	42.3	16	46.4	14	63.0	13	6.1	7	0.4	3	0.7	2
Lake States	11.5	14	33.5	12	44.9	14	66.0	14	15.5	17	0.2	2	4.7	16
Corn Belt	8.2	10	28.5	11	44.1	14	110.4	23	6.5	7	0.0	0	0.8	3
Delta States	8.4	10	35.2	13	38.0	12	53.5	11	16.0	18	1.1	9	3.0	10
Southeast	18.8	23	51.1	19	53.0	16	66.8	14	21.9	24	0.8	7	2.6	9
Appalachian	10.5	13	36.5	14	43.8	14	56.7	11	9.4	11	0.8	7	3.1	10
Northeast	9.2	11	29.0	11	38.0	11	42.7	8	12.9	14	0.4	3	1.0	3
	81.7		268.3		324.5		490.3		89.8		12.0		30.1	

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*Totals may not add because of rounding.

[1] Includes SCS‡ Class IV Permanent Pasture, Forest, Range.

[2] Includes SCS Classes I-IV Permanent Pasture, Forest, Range.

[3] Includes SCS Classes I-IV Permanent Pasture, Forest, Range, Rotation Hay and Pasture, Hayland and Open Land Formerly-cropped.

[4] Includes SCS Classes I-IV Permanent Pasture, Forest, Range, All Cropland except that in Conservation Use Only.

[5] Includes SCS Classes II_W-IV_W Permanent Pasture, Forest, Range.

[6] Includes USFS‡ Classes I-III National Forest System Land.

[7] Includes USFS Classes I-IV National Forest System Land.

‡SCS (Soil Conservation Service of USDA) Classification System, classifies the soils according to quality: Class I is best and Class VIII is unsuitable for cultivation. The USFS Classification is similar.

Note: In another independent study (ref. 3, p. 42) it was estimated that about 270 x 10^6 acres of land suitable for biomass production could be withdrawn for this purpose from pasture and forest land.

Table B-3. A Comparison of Capital Investments for Alcohol Production Plants Based on Natural Gas, Coal and Wood Waste(52)

Product	Raw Material	Conversion Method	Production Cap. MLPY	Plant Investment '75 Million $
Methanol	Natural Gas	Reaction with steam to syngas, its conversion to methanol	189 (50 MGPY)	23.1
			756 (200 MGPY)	61.0
	Wood Waste	Partial oxidation to syngas in a Moore-Canada reactor	189	64
			756	169
	Coal	Gasification to syngas	189	74.4
			756	178
Ethanol	Ethylene from natural gas	Catalytic reaction with water	94.5 1900 (25 MGPY)	20
			378 (200 MGPY)	53
	Corn	Dilute acid hydrolysis of starch to dextrose and its fermentation to ethanol	94.5	25
			378	66
	Wood Waste	Dilute acid hydrolysis of cellulose to glucose and its conversion to ethanol	94.5	70
			378	185

Table B-4 Price of Producing Ethanol from Wood in a Multiproduct Mode Based on Dry Wood @ $34/ton(52,35,36)

Product & Co-Products	Conversion Method	Input MTPY	Ethanol Output	Selling Price	Market Price
Ethanol, Furfural, Phenol (the latter two sold @ 65% Selling Price)	Prehydrolysis of hemicellulose; acid hydrolysis of cellulose and finally hydrogenolysis of Lignin	0.548 softwood	94.5 MLPY (25 MGPY)	0.407/L (1.54/G)	Ethanol from Ethylene
		0.548 Hardwood	94.5 MLPY (25 MGPY)	0.339/L (1.28/G)	0.265/L (1.00/G)

Table B-5. A Comparison of the Economics of Producing Ammonia and Methanol from Natural Gas, Coal and Wood*

		Exxon's Projections(82)			Mitre Corp's Projections (4,11)		
			From Coal			From Wood	
Product	Year	From NG* 1980 $	Plant Size	Price 1980 $	From NG 1976 $	Plant Size	Price 1976 $
Ammonia	1985	220/T	0.73	227/T	150-250/T	0.18	135/T
	2000	248/T	MTPY	227/T	275-450/T	MTYPY	130/T
Methanol	1985	0.18/L (0.68/G)	832 MLPY (220 MGPY)	0.177/L (0.67/G)	0.185-0.225/L (0.70-0.85/G)	140 MLPY (37 MGPY)	0.198/L (0.75/G)
	2000	0.206/L (0.78/G)		0.177/L (0.67/G)	0.344-0.432/L (1.30-1.60/G)		0.185/L 0.70/G)

*Based on products obtained via new and improved coal gasification method from $21/ton Illinois coal and from gasification of wood starting at price $32/ton dry wood and subsequent price reduction due to improved production modes.

NG = Natural Gas

Table B-6. Methanol and Formadehyde Production from Biomass -- Comparative Data

Product	Conversion Method	Plant's Input Dry Wood MTPY*	Product Output	'75 Selling Price $	'75 Market Price $
Methanol	Gasification of biomass via partial oxidation in Moore-Canada reactor to syngas and catalytic transformation of syngas to methanol	0.54	189 MLPY (50 MGPY)	0.259/L (0.98/G)	Methanol from natural gas
		2.19	576 MLPY (200 MGPY)	0.221/L (0.83/G)	0.100/L (0.38/G) Coal methanol also has low price
Formaldehyde	Catalytic oxidation of wood methanol	Methanol Feed	37% Solution		
		0.100/L (0.38/G)	4.53 MKgPy (10 MLbPY)	0.358/Kg (0.162/lb)	Formaldehyde from gas methanol
		0.127/L (0.48/G)	4.53 MKgPY (10 MLbPY)	0.397/Kg (0.180/lb)	0.238/Kg (0.108/lb)
		0.100/L (0.38/G)	45.3 MKgPY (100 MLbPY)	0.22/Kg (0.10/lb)	0.238/Kg (0.108/lb)
		0.127/L (0.48/G)	45.3 MKgPY (100 MLbPY)	0.263/Kg (0.119/lb)	

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*MLPY = Million Liters Per Year; MKgPY = Million Kilograms Per Year; MTPY = Million Tons Per Year; G = U.S. Gallon; and, L = Liter. MLbPY = Million Pounds Per Year

Table B-7. Price of Chemicals from Wood and Corn in a Single Product Mode Based On: Dry Wood @ $34/ton, Corn $3/bushel, 30% Profit on Investment(52,35,36)

Product	Conversion Method	Plant's Input Dry Wood MTPY	Product Output	'75 Selling Price $	'75 Market Price $
Sugar	Dilute acid hydrolysis of wood to glucose	0.54	180,000 TPY	0.296/Kg (0.134/lb)	0.121/Kg (0.055/lb)
		2.19	710,000 TPY	0.212/Kg (0.096/lb)	0.121/Kg (0.055/lb)
Ethanol	Fermentation of glucose obtained from acid hydrolysis of wood	0.54	94.5 MLPY (25 MGPY)	0.50/L (1.90/G)	Ethanol from petroleum derived ethylene 0.30/L (1.20/G)
		2.19	378 MLPY (100 MGPY)	0.375/L (1.42/G)	
	Fermentation of dextrose obtained from acid hydrolysis of cornstarch		94.5 MLPY (25 MGPY)	0.375/L (1.43/G)	
			378 MLPY (100 MGPY)	0.325/L (1.23/G)	
Furfural	Dilute acid hydrolysis of hardwood's hemicellulose and subsequent transformation	0.278	6.8 MKgPY (15 MLbPY)	1.88/Kg (0.85/lb)	Furfural from corn-cob, cereal straw
		0.73	18.1 MKgPY (40 MLbPY)	1.35/Kg (0.61/lb)	0.82/Kg (0.37/lb)

MLbPY = Millions pounds per year

Table B-8.

Characteristics of Pyrolysis Reactors (83)

I	VERTICAL FLOW REACTORS	
	Direct Heat Transfer	Indirect Heat Transfer
	• Moving packed bed (shaft furnaces) • Moving, staged, stirred bed (multiple hearth furnaces) • Entrained bed (transport reactors)	• Moving packed bed (shaft furnaces) • Entrained bed (recirculating heat carrier)
II	FLUIDIZED BED REACTORS	
	Direct Heat Transfer	Indirect Heat Transfer (recirculating heat carrier)
III	HORIZONTAL OR INCLINED FLOW REACTORS	
	Direct Heat Transfer	Indirect Heat Transfer
	• Tumbling solids bed (rotary kilns) • Agitated solids bed (on conveyor)	• Tumbling solids bed - Rotary calciners - Rotary vessels (recirculating heat carrier) • Agitated solids bed (on conveyor) • Static solids bed (on conveyor)
IV	MOLTEN METAL OR SALT BATH REACTORS	
	Numerous flow and mixing options	
V	MULTIPLE REACTOR SYSTEMS	
	Numerous flow and mixing options	
VI	BACK-MIX FLOW REACTORS	
	For slurries and melts	

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*Some reactors may be designed with numerous solids and gas flow regimes (countercurrent, cocurrent, split flow, crossflow).

†Also known as fixed bed reactors.

Table B-9. Pyrolysis Reactor Classifications (English Units) (43)

	Heating Method		Product Distribution			Feed Conditions				Status		
	Dir.	Indir.	Solid (BTU/lb)	Liquid (BTU/lb)	Gas (BTU/ft3)	Raw	Size Red.	Separation	Reactor Temp C	Res.	Pilot PLT (TPD)	Comm (TPD)
VERTICAL SHAFT												
Garrett		X	9,700	10,500	550		X	X	900		4	200
Battelle	X	X			170		X		1800		2	
Gr. Tech.	X		10,000	13,000	200		X		750		25	
URDC	X				150	X			2600		120	
Torrax	X				150	X			3000		75	
Union Carbide	X				300	X			3000		5	200
HORIZONTAL SHAFT												
Kemp		X	X	X	X		X		1100		5	
Barber-Colman		X			500		X	X	1200		1	
ROTARY KILN												
Monsanto	X		2,500		130		X		1800		35	1000
Devco	X		X		X		X	X	1000		120	1500
Rust Eng		X			450				1250			260
Pan Am Res.		X					X		200	X		
FLUID, BED												
W. Virginia		X			450		X	X	1400	X		
A. D. Little		X			X		X	X		X		
Coors	X				150		X	X	1400		1	
OTHER												
Battelle		X							1800	X		
Hercules			X							X		
Bur. Mines		X			500		X	X	1800	X		
NYU		X							1700	X		
USC		X								X		
Anti Poll. Syst.										X		
Univ. Calif.		X					X			X		
Wallace-Atkins		X	3,000	16,000	500				1600	X		
Res. Sci.		X					X		1800		2	

Table B-10. Comparison of Pyrolysis Concepts (43)

	Refu-Cycler	Occidental	Purox	Landgard
Input Capability	Trash & Sludge	Dry Trash	Trash & Sludge	Trash & Sludge
Pre-Processing Requirements	None; some sorting of large objects required	Drying, Shredding Classification Pulverizing	Shredding; needs currently being studied	Shredding
Products	150 Btu/ft^3 gas glassy aggregate	Heavy fuel oil ferrous metals glass	300 Btu/ft^3 gas glassy aggregate	Steam ferrous metals, char, glassy aggregate
Energy Yield	64%	27%	64%	41%
Auxiliary Fuel Required	Propane (startup only)	5 lbs/ton of #2 fuel oil	Propane (startup only)	51 lbs/ton of #2 fuel oil
Electric Power Required	42 kwh/ton	140 kwh/ton	120 kwh/ton	67 kwh/ton
Development Power Required	10 ton/day unit under construction evaluation began late in 1976	4 ton/day pilot plant 200 ton/day pilot plant under construction	5 ton/day pilot plant in 1971 200 ton/day pilot plant in operation since 1974	35 ton/day pilot plant in 1972 1000 ton/day pilot plant in 1973; further evaluation to occur during 1977
Capital Cost*	$10,000/ton-day for 100 ton/day size (Sept. 1976)	$56,000/ton-day for 200 ton/day size (June 1976)	$14,000/ton-day for 1,000 ton/day size (Oct. 1974)	$26,000/ton-day for 1,000 ton/day size (June 1976)

*Cost of Refu-Cycler and Purox are engineering estimates, costs for Occidental and Langard are those incurred in their original installations and include considerable design modification costs and performance guarantees.

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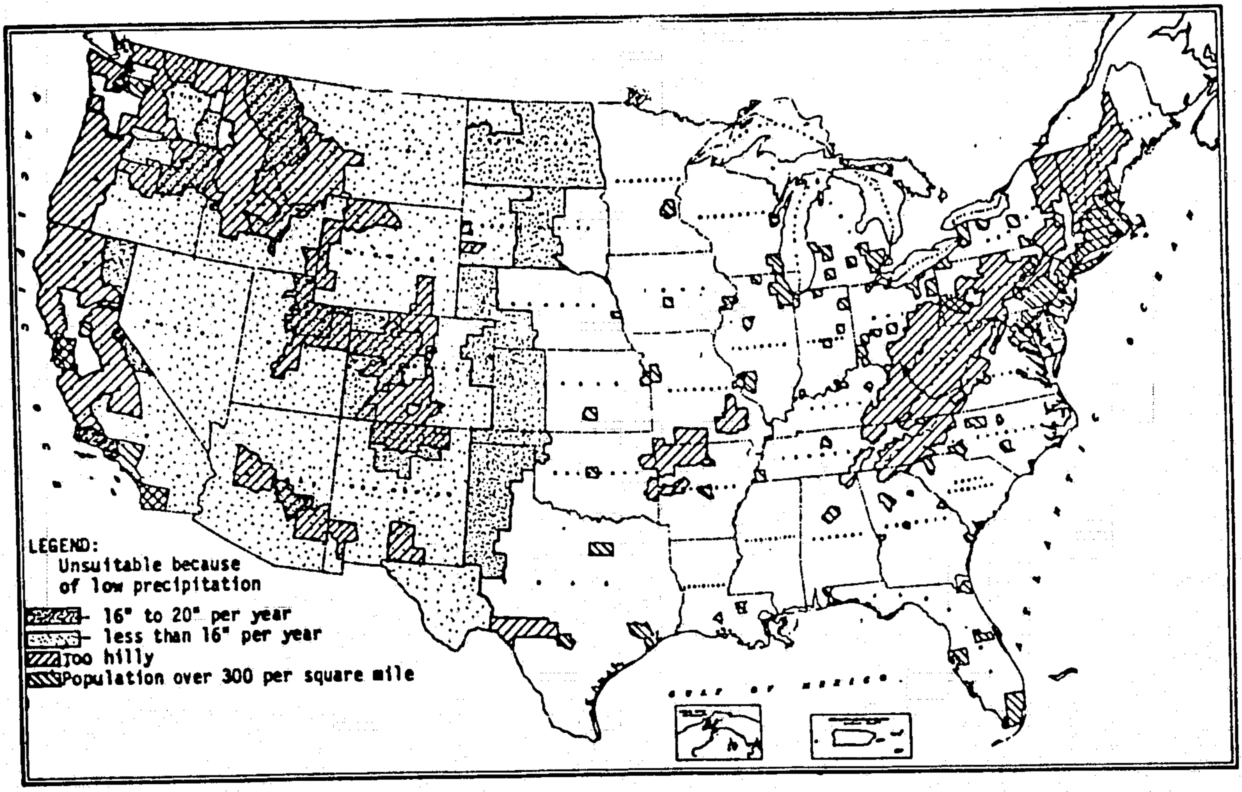

Figure B-1. Territory unsuitable for Energy Plantations TM (11)

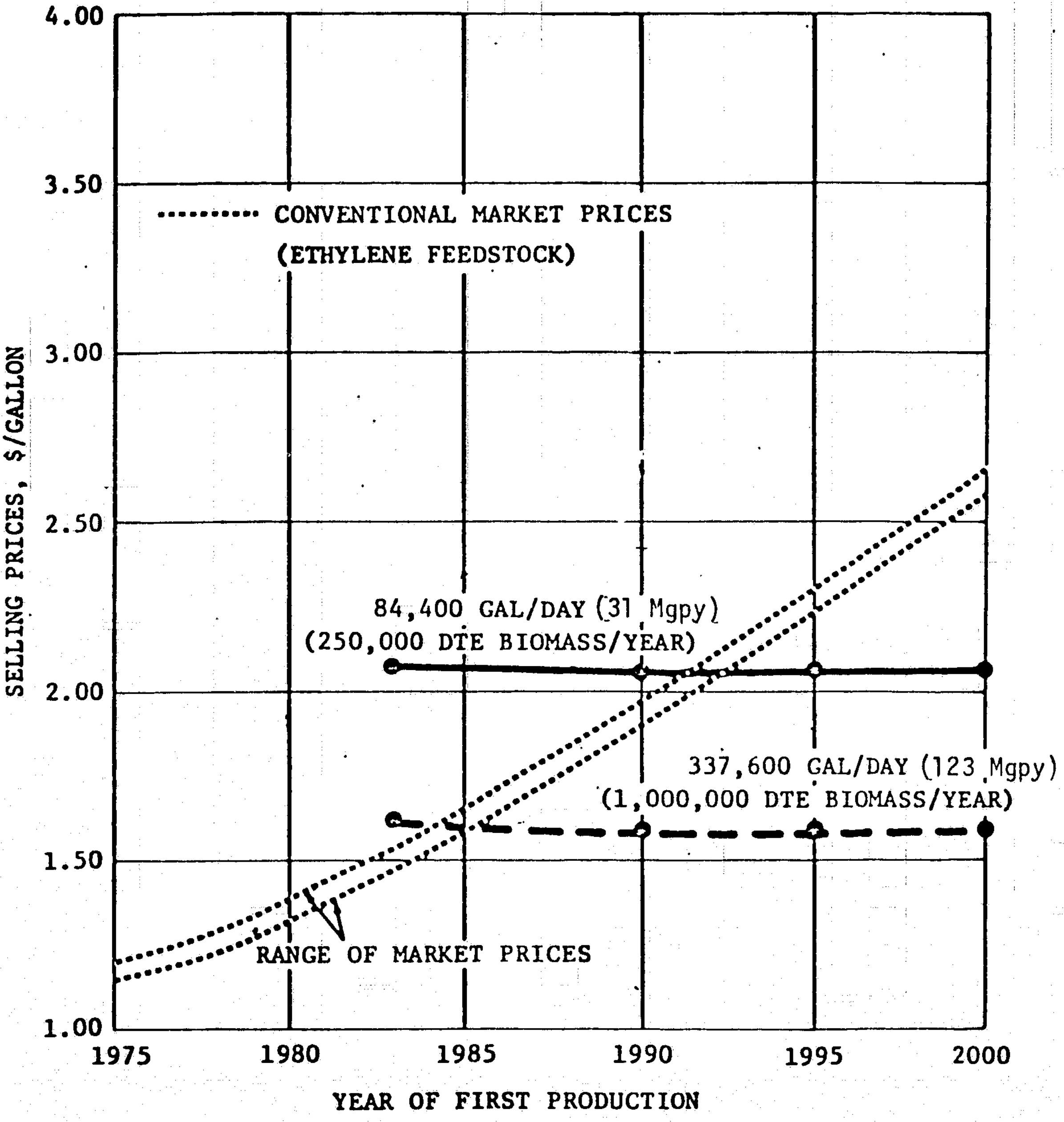

Figure B-2. Comparison of Market and Production-Oriented Selling Prices for Ethanol (4)

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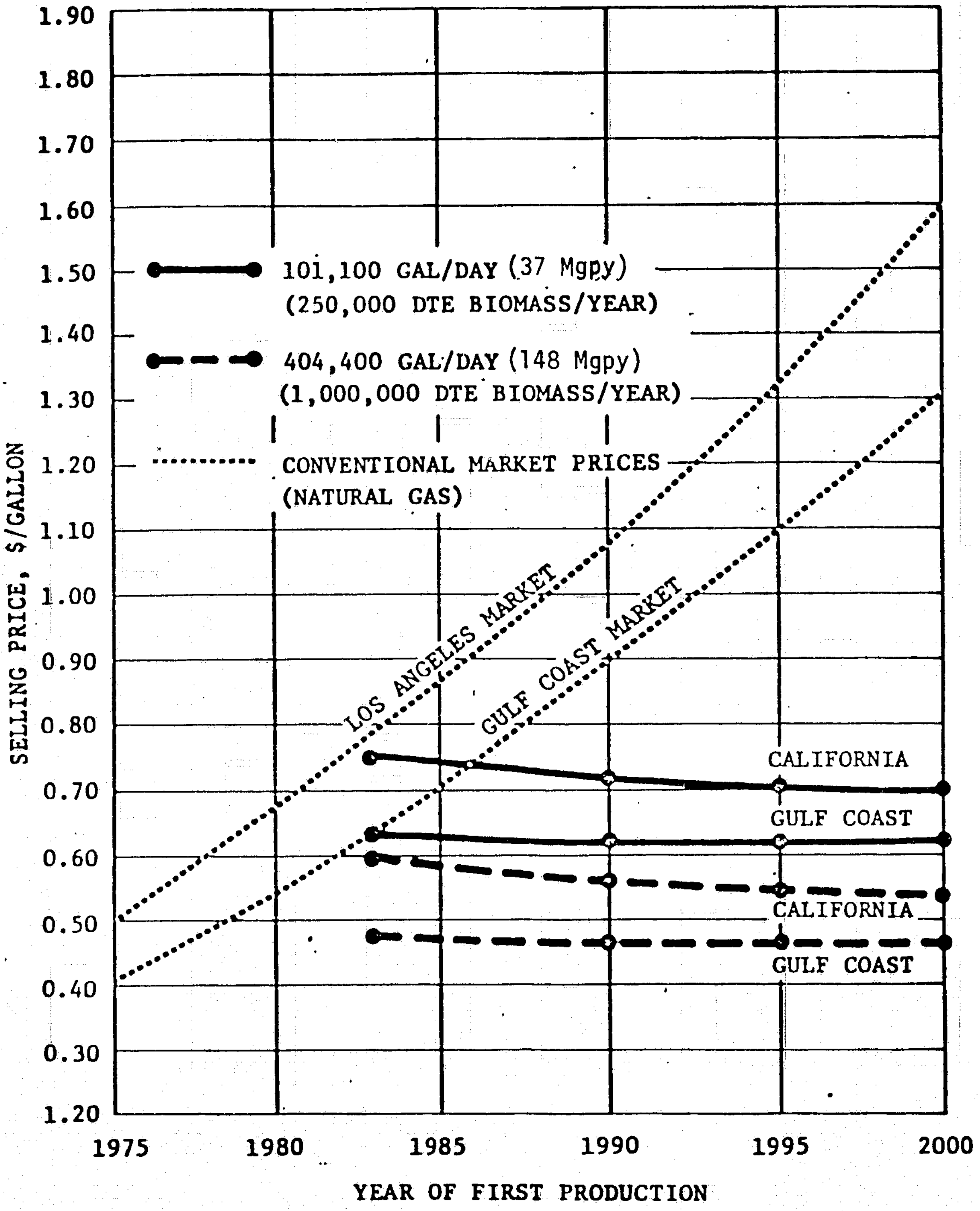

Figure B-3. Comparison of Market and Production-Oriented SellingPrices for Methanol (4)

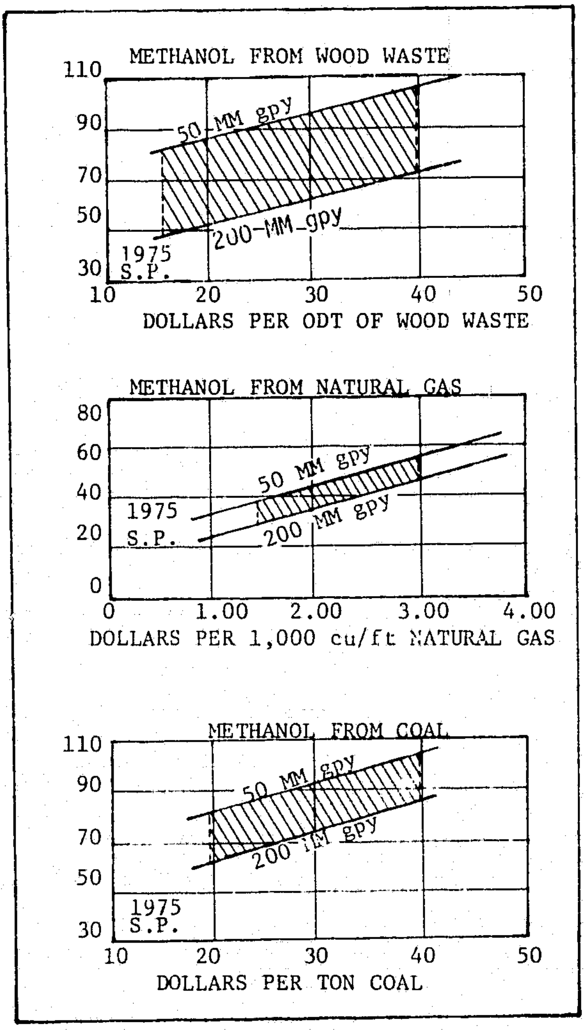

Figure B-4. Methanol Selling Prices, 1975 $, (52)

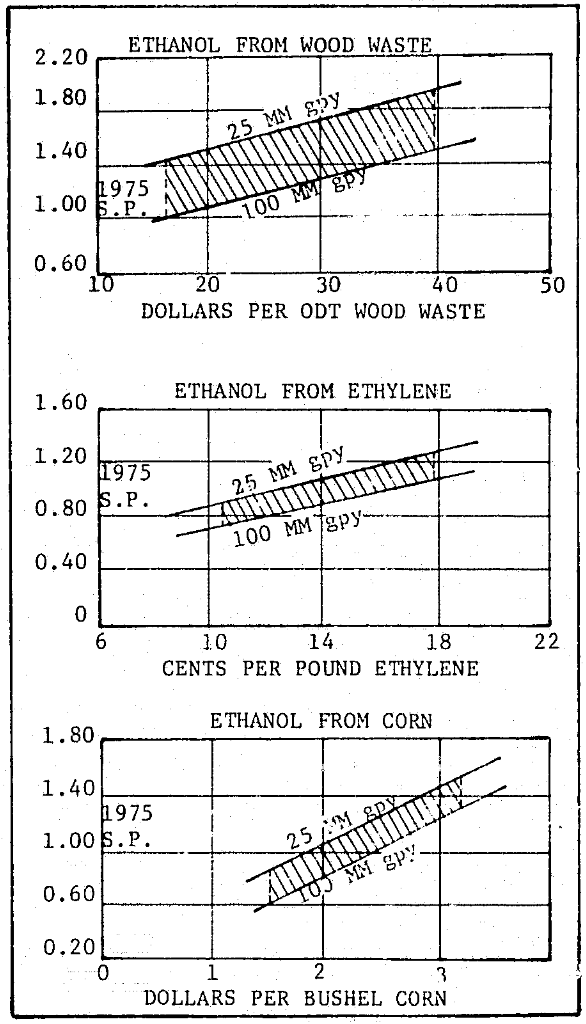

Figure B-5. Ethanol Selling Process 1975 $, (52)

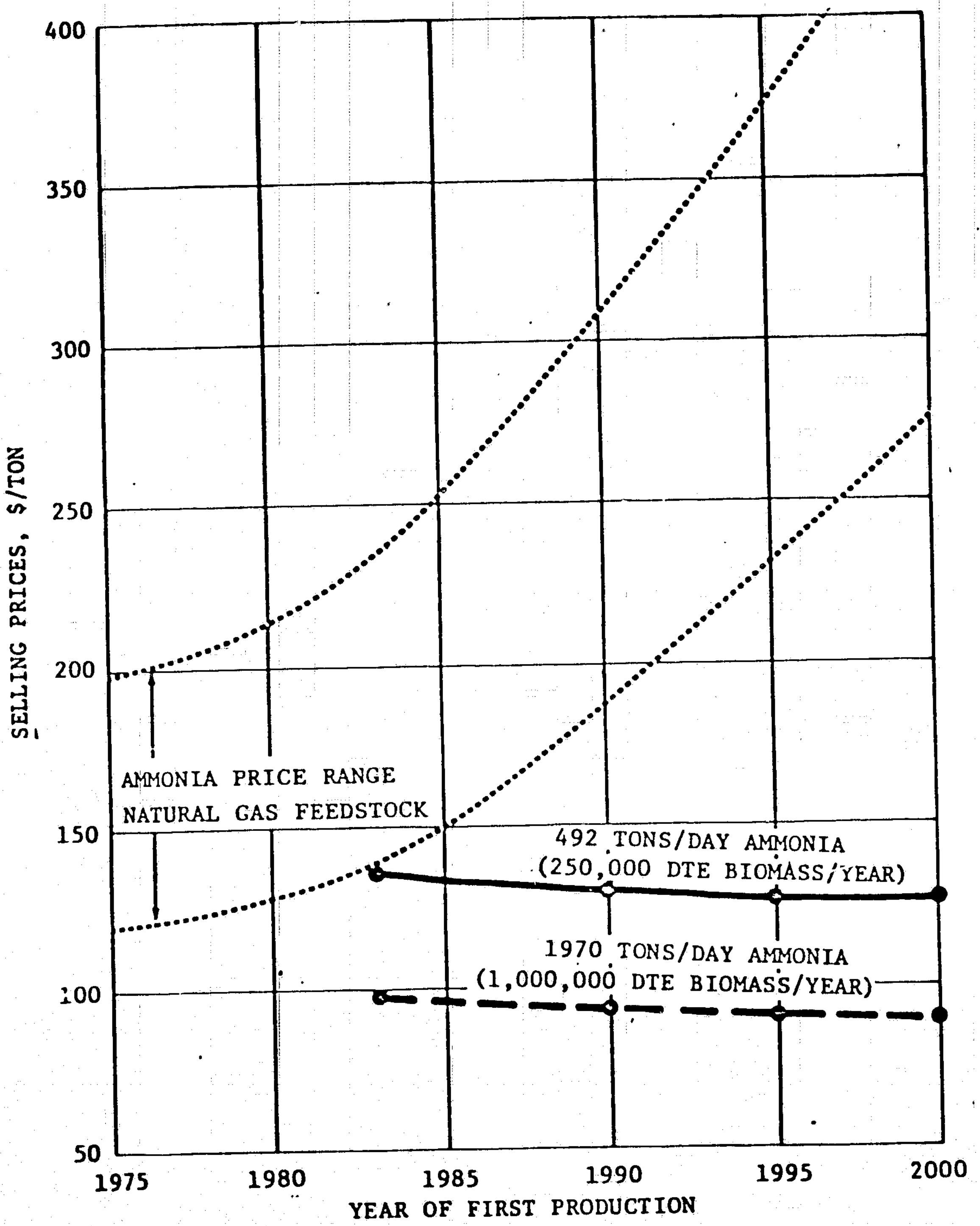

Figure B-6. Comparison of Market and Production-Oriented Selling Prices for Ammonia (4)

NASA—JPL—Coml., L.A., Calif