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Biotechnology for Producing Fuels and Chemicals from Biomass: Recommendations for R&D

Volume I — Synopsis and Executive Summary

Ruxton Villet

SERI

Solar Energy Research Institute
A Division of Midwest Research Institute

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BIOTECHNOLOGY FOR PRODUCING FUELS AND CHEMICALS FROM BIOMASS: RECOMMENDATIONS FOR R&D

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FOREWORD

This overview was prepared for the Department of Energy under Contract EG-77-C-01-4042, Task 3370. It is in two volumes. The purpose of Vol. I: Synopsis and Executive Summary is to provide a framework for the design of a national program of contracted research in biotechnology for the production of fuels and chemical feedstocks from biomass. For Vol. II: Selected Topics on Biotechnology R&D for the Production of Fuels and Chemicals from Biomass, detailed literature surveys have been undertaken. The material in Vol. II can serve as a guide to research scientists and engineers interested in entering the field of energy biotechnology. Thanks are due to the consultants who assisted in literature surveys and process evaluations; their names appear with specific chapters of Vol. II.

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SYNOPSIS

To produce from biomass various fuels and chemical feedstocks that will sell competitively in the open market, it is crucial to develop a Biotechnology of Biomass Processing. The economic incentive of biotechnological processing is marginal at present, but the potential of a sustained level of effort in research, development, and demonstration is considerable.

In Volume I of this report, specific research and development project areas are identified as avenues to attractive biotechnological goals. These areas are discussed in greater depth in Volume II, with detailed references from science and engineering literature.

Biotechnological processes involve the harnessing of biosynthetic capabilities of lower organisms such as bacteria, yeasts, fungi, and algae. These microorganisms have incredible versatility for converting chemical substances to products of commercial value. One of the oldest biotechnological processes is yeast fermentation for the production of ethanol from sugars. Other bulk chemicals, such as butanol, acetone, acetic acid, and lactic acid, have also been manufactured fermentatively (using bacteria) on a large scale. Fungi and algae produce organic chemicals of commercial interest. For example, certain algal species synthesize hydrocarbons. Complicated molecular structures such as antibiotics can be synthesized by microorganisms in one step, whereas involved multiple reactions are required in chemical synthesis. Biotechnological and chemical synthetic processes can be linked: chemicals produced by fermentation can serve as feedstocks for further conversion by chemical reaction, or vice versa.

When first introduced, industrial microbiology for producing chemicals developed vigorously. But, except for the production of novel pharmaceuticals, the industry largely went into abeyance several decades ago, unable to meet the challenge of cheap petroleum and cracking technology. Hydrocarbon costs are mounting, however, as the fraction of U.S. oil supplied by other countries becomes larger. To seek substitute commodities in response to market forces is the lifeblood of the chemicals industry. It is likely, therefore, that the microbiological production of chemicals will again become a commercially profitable technology.

For example, fermentation ethanol can serve as a fuel and as a basic chemical for synthesizing other products. Ethylene, currently produced from petroleum, is a prime chemical feedstock; its major derivatives are polyethylene, ethylene oxide, vinyl chloride, and styrene. The supply is becoming tighter, but the demand is unabated and thus the price is rising. It is possible, however, to produce ethylene from ethanol. At some time the economic incentive will be sufficient for displacement of petroleum-derived ethylene by fermentation ethanol. Ethanol can be a feedstock for butadiene, acetaldehyde, and acetic acid production. Thus, a plastics industry based on renewable resources is quite feasible.

In general, the innovation needed for a technological substitution is considerable and expensive. Feasibility of a new technology usually can be demonstrated on a small scale without undue expenditure and lapse of time. Scale-up to commercial dimensions, however, involves costly engineering research and development and considerable time. Biotechnological processes, however, are an exception. Since costs of transporting biomass are high, small decentralized plants drawing on biomass resources close at hand are preferable to large, capital-intensive operations. Moreover, fermenters of lower unit capacity are favored because they are more readily controlled and optimized. The net result is

that the degree of scale-up required, and hence the lead time for technological development, is reduced. It is very likely, therefore, that the break-even cost for a biotechnology of biomass processing will be considerably lower than for other energy technologies.

Two directions for R&D are recommended:

- Revival of previously developed fermentation technology, with efficiency improved to bring the processing costs to a competitive level; and
- Development of entirely novel biotechnological processes, a longer-term endeavor.

When the use of fermentation processing to produce industrial chemicals was discontinued, equipment was left dormant. For example, 500,000-gallon fermenters, originally designed for producing a mixture of chemical solvents (butanol, acetone, ethanol), have been idle for almost 30 years. This fermentation capacity could become useful again, but the efficiency of production must be improved. The economic incentive for modernizing existing equipment must of course be weighed against the benefits of constructing new facilities.

The fermentation processes previously developed employed readily fermentable feedstock, such as molasses, sugar cane juice, corn, grain, and sorghum; but the cost of such material (except for wastes from the food and paper pulp industries) is high. In addition, a low rate of production and batch-type processing, low concentration of product, energy inefficiency of product recovery, and inadequate process control are problems. Appropriate techniques and recent discoveries of microbial genetics and biochemical engineering can be applied to solve these problems. Specific R&D opportunities are identified in the Executive Summary (Vol. I) and elaborated in Vol. II. Moreover, a scheme of SERI/DOE cooperation with private industry is proposed for the commissioning of virtually ready-made Process Demonstration Units (PDUs).

An endeavor of somewhat longer lead time is the direct conversion of woody and herbaceous biomass. An attractive feature of this form of biomass in contrast to readily fermentable feedstocks is the relatively low cost. The biotechnology for their conversion is at a rudimentary stage, however, and the cost is high. Only one biotechnological process for the conversion of lignocellulose has been operated successfully at a scale considerably larger than bench scale: the Gulf Oil/University of Arkansas process. Biotechnology for extracting fuels and chemicals from algal or fungal biomass should also be developed.

Emphasized in this summary are the considerable advantages of the newly emerging techniques of genetic engineering, such as gene-splicing and cloning for the development of bioconversion processes. With such methods, biosynthetic capabilities of living organisms can be harnessed and tailored with unprecedented success. Chiefly as yet confined to research in medical biochemistry, techniques of genetic engineering are readily applicable to biotechnological processing.

Coupled with the need for research in genetic engineering is the need for new developments in biochemical engineering, such as bioreactor technology and process control. The objective is to design processes taking best advantage of the improved performance of new microbial hybrid strains. For example, a more rapid synthesis of microbial products narrows the optimal ranges of process variables, thus requiring more refined chemical engineering design and more precise control.

The R&D in a field as highly diversified as the biotechnology of biomass processing must have a multidisciplinary basis. It is recommended, therefore, that biotechnological strategy be organized as the integrated effort of the following three disciplines:

- Biochemical Engineering,
- Microbial Genetics, and
- Biochemistry.

Basic and applied research, both theoretical and experimental, would be conducted in all three disciplines. The Biochemical Engineering group would perform process economic evaluations and determine process goals of the other groups, hence providing an overall guide for R&D planning. Another responsibility of the engineers would be to generate design information using mathematical modeling and to perform bench- and pilot-scale work for the purpose of constructing PDUs. The process economic evaluations and the generation of design data for biotechnological processes would depend heavily on experimental information supplied by the Genetics and Biochemistry groups. Biotechnological R&D based on such collaboration is being set up at the Solar Energy Research Institute (SERI).

The design and management of a national program of R&D to establish a biotechnology of biomass processing is discussed in Section 3.0 of the Executive Summary. To facilitate management of the program, the contractual work could be arranged under the following categories:

- Microbiological Research and Development;
- Biotechnological Process Evaluation, Control, and Optimization;
- Biotechnological Process Development and Demonstration; and
- Design and Development of Separations Processes.

A biotechnological renaissance for producing energy and a renewable resources chemical industry could occur soon. Another potential advantage of biotechnology is implicit in its highly diversified nature: as the new technology gains momentum, many of its novel techniques might be applied to other areas, such as the pharmaceutical and food industries. The possibilities for investment and commercial development resemble the promise of the computer and microelectronics industry a few decades ago.

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SECTION 1.0

GENERAL OVERVIEW AND RECOMMENDATIONS

1.1 INTRODUCTION

There is a growing incentive to produce from biomass various fuels and chemical feedstocks that will sell competitively in the open market. To achieve this objective, efficient biotechnological processes are needed. The economic incentive for biotechnological processing is marginal at present, but, as the supply of petroleum-based fuels and chemicals becomes tighter and prices rise, market forces for product substitution will become increasingly important.

The purpose of this report is to identify areas of research and development that must be pursued so that the technical basis for a biotechnology of biomass processing can be established as soon as possible.

Biotechnology encompasses several diverse disciplines, ranging from research in molecular genetics to design of industrial plants. A research, development, and demonstration program is necessary to integrate these various disciplines into an effective structure.

1.2 RECOMMENDED DESIGN OF R&D PROGRAM

Two general goals for R&D are recommended:

- The near-term revival and improvement of conventional, although currently dormant, fermentation technology (for producing ethanol, butanol, acetone, acetic acid, and glycerol, for example); and
- The long-term development of a new "biotechnology" for producing fuels and chemicals efficiently from biomass.

For both the near and long terms, two mutually supporting research objectives are stressed:

- The genetic engineering of microorganisms so that biochemical and physiological capabilities of biotechnological potential are introduced or amplified; and
- The commercial exploitation of these capabilities through optimal process design, scale-up, and control.

Discussed in this section are two areas ripe for application to these objectives:

- Genetic Engineering, and
- Chemical and Biochemical Engineering.

1.2.1 Genetic Engineering

As pointed out by Max Delbrück, Nobel laureate and pioneer in molecular genetics, the genetic devices that have evolved in nature are unsurpassed by technology in their

abilities for the storage, replication, and readout of information. This biological information and the biochemical processes it controls can be harnessed for the biotechnological exploitation of microorganisms. To improve these biosynthetic capabilities, industrial microbiological processes have thus far employed, in general, the classical methods of microbial strain selection and development. Another technique is induced mutagenesis using, for example, chemicals or irradiation; however, the mutations are random and not controlled easily. More promising methods are techniques of gene transfer.

Of the various techniques of gene transfer, the method involving recombinant DNA and cloning, known as "genetic engineering," yields the most fruitful and rapid results. Use of this recently developed method is almost wholly confined as yet to work in medical biochemistry. For example, chains of the mammalian hormone insulin can now be synthesized by bacteria. A recent impressive success in genetic engineering was the production of the human hormone somatostatin achieved by programming a bacterial host. Previously, production of a few milligrams required the laborious extraction of the hormone from the homogenized brain tissue of half a million sheep. Genetic engineering methodology is beginning to penetrate research in developmental biology and may elucidate the molecular basis of cancer. Striking advances in specific fragmentation, cloning, and sequencing of DNA are being made.

Commercial use of this new technology is emerging. In the United States several private companies (Cetus, Genentech, Genex) have been formed. DuPont is establishing a molecular genetics program incorporating recombinant DNA techniques: a high containment laboratory to comply with NIH guidelines is being set up.

The inclusion of genetic engineering technology in an R&D program for the biological conversion of biomass undoubtedly will have a pronounced impact. For example, a particular biotechnologically desirable conversion capability could be transferred from a slow-growing species to a fast-growing species. Or a microbial strain might be constructed with an expanded metabolic repertoire so that the microorganisms could convert pentose sugars (from hemicellulose) as well as hexoses (from cellulose); this would lead to an enhanced yield of ethanol from wood polysaccharides and greater rates of production. Yet another possibility is the construction of an organism that can hydrolyze polysaccharides as well as ferment the resultant sugars with the high yields of yeast; the elimination of an enzyme-producing step could reduce the cost of production of ethanol. Genes from microorganisms that grow at high temperatures could be tranferred to other species of biotechnological merit.

It can be argued that it is a risky venture to embark on gene-transfer work using donor and/or recipient strains for which the genetics and genetic regulations are not known. Long-term fundamental studies such as gene-mapping experiments and gene-control analyses should be supported. At the same time, however, experiments on gene transfer can have a fruitful biotechnological outcome. At the very least, for example, strain compatabilities will be examined for various donor/recipient combinations. Moreover, in vitro recombinant DNA experiments will add to the genetic knowledge of the strains involved.

Certain fungi and algae produce relatively large concentrations of organic chemicals that could be harvested as fuel and/or chemical feedstocks. Such biosynthetic capability could be enhanced by genetic engineering, providing that appropriate gene-transfer systems were developed. Interspecies transfer of genes is also possible.

Marine organisms also have biotechnological potential. (Moreover, the growing shortage of fresh water could limit production of terrestrial biomass.) Genetic manipulation of marine bacteria and plankton is an untouched field as yet. Recently it has been demonstrated that there is genetic recombination in phytoplankton.

Genetic engineering could accelerate the development of higher plant biomass for bioconversion. Plant breeding is a slow process—many generations are needed to introduce new traits into suitable varieties. It could be of biotechnological advantage to transfer traits between different species. For example, the heightened photosynthetic efficiency of tropical plants might be transferred to temperate zone varieties. Vector DNA can be transferred using plant viruses or bacteria with tumor-inducing episomes. Accompanying developments in plant cell culture are required to implement these techniques.

Apart from biomass production for purposes of bioconversion, fuels might be harvested directly from oil-forming arid-zone plant species such as Euphorbia (e.g., work of Nobel laureate Melvin Calvin). Such a process requires assessment as a biomass production/extraction system. The promotion of work with higher plants must be based on a thorough technical and economic comparison of higher-plant and microbial routes to biosynthetic chemical products.

The inherent dangers in genetic engineering R&D have been the subject of much public discussion. Not long ago Louis Pasteur's work experienced similar interference, and if it had persisted, medical and industrial microbiology might never have developed. The National Institutes of Health (NIH) guidelines require that certain experiments be performed in high-containment laboratories. NIH has renovated a facility located at the Frederick Cancer Research Center to provide a high-containment laboratory of 15,000 ft^2. The NIH guidelines are steadily being relaxed because the dangers of pathogen formation are remote. For example, the strain of enteric bacteria used in genetic engineering work has lost the capacity to propagate in the gut; it requires special laboratory media.

Gene-splicing and cloning techniques are flourishing in laboratories of the United States and Europe. We recommend a strong commitment to use of this newly developing discipline in biosolar energy R&D.

1.2.2 Chemical and Biochemical Engineering

The development of chemical engineering grew from the need to scale up chemical reaction experiments to the level of commercial processes by taking into account complexities due to heat-, mass-, and momentum-transfer. It is a multidisciplinary field in which chemistry, physics, and mathematics are drawn together. Biochemical engineering has evolved from the need in the design of commercial biotechnological processes for combining the techniques of biochemistry, microbiology, physiology, and genetics with those of chemical engineering.

One particular advantage of biotechnological processing is its suitability for small-scale operation. Fermenters of lower unit capacity are favored because they are more readily controlled and optimized. Moreover, plants will be smaller to match the regional supply of biomass in decentralized biomass conversion systems. Large capital-intensive operations (such as for coal and oil shale) will not be required for biomass processing. The lower degree of scale-up needed for biotechnological processing of biomass will reduce the lead time and entry fee of this new technology.

A firm investment in biochemical engineering, as well as in genetic engineering, can hasten attainment of the goal of producing fuels and chemical feedstocks from biomass. Some examples are considered in this subsection.

1.2.2.1 Chemical Engineering Separations Processes

Conventional Separations Processes. To lower the cost of ethanol production and make the process energy-efficient, the separation of ethanol from water by distillation must be improved. About 70% of the steam costs in an ethanol plant can be attributed to the distillation section. It is necessary to work on alternative, unconventional methods of ethanol recovery, but there is an immediate need to push conventional separations processes to their technological limits. Chemical engineering unit operations must be regarded in a new light.

Distillation or fractionation, as a chemical engineering unit operation, was developed chiefly through its applications in the petroleum refining industry. Stage-wise operations, as still used today, are unattractive in terms of energy utilization. They function too far from equilibrium with large changes in entropy. A thorough thermodynamic and chemical engineering design analysis could reveal several possibilities for improvement.

Unconventional Separations Processes. In parallel with improvement of conventional processes, novel separations processes must be developed. For membrane separation work, emphasis should be placed on designing new types of membranes as well as adapting available membranes. Experimental data are needed on adsorption and extraction for recovery of fermentation products. The technology of vacuum fermentation should be developed.

1.2.2.2 Bioreactor Design

Conventional Bioreactors. While yet retaining conventional industrial process design, fermenter operation can be significantly improved with process modeling, control, and dynamic optimization.

On-line computers are designed to log data, to analyze the data using appropriate algorithms, and, finally, to control process variables. The necessity for applying microcomputers or microprocessors in fermentation technology increases as improved microbial strains are developed because the rates of feedstock and product mass-transfer increase and optimal ranges of process conditions narrow.

The effectiveness of control strategies depends on the validity of the kinetic and hydrodynamic models adopted. Problems of the mathematical modeling must be resolved, such as the choice of a function relating growth rate of microorganisms to substrate concentration.

Sensitive and precise instrumentation for computer process control is an absolute necessity. For example, it is possible to determine the respiration rate of a culture in a fermenter by knowing inlet and outlet gas compositions, flow rates, and cell density. The computer cannot make a meaningful control decision unless these parameters are measured precisely. The development of new instruments is within the scope of a program of biotechnology of biomass processing.

Unconventional Bioreactors. To improve processing efficiency, continuous processing should supplant batch operation. A problem with conventional continuous fermentation operation, however, is that the rate of throughput is limited by the maximum specific growth rate of the organism. To circumvent this limitation and permit greater production rates, bioreactors could be designed in which cells are immobilized. A possible avenue is to develop strains of microorganisms that flocculate. Another way is to imbed cells in polymers and form biocatalyst pellets.

Novel fermentation vessel geometries are being developed, chiefly in Europe and Japan. Some examples are the air-lift, completely mixed microbial film, cyclone tower, hollow-blade aeration, and tubular-loop designs. This area of biochemical engineering is just gathering momentum.

The development of commercial bioreactors for converting insoluble materials, such as cellulosic and hemicellulosic biomass, demands new approaches in biochemical engineering design. Effective packed-bed reactors for chemicals processing have been designed, for example, by describing residence-time distributions and the effects on conversion with suitable mathematical modeling. However, a disappearing solid phase, as encountered in biomass reactors, introduces complexities that have not yet been treated satisfactorily.

For the transfer of biomass in slurries to bioreactors, pipelines and pumping systems have to be sized. Adequate quantitative information on rheological behavior must be accumulated, particularly in regard to time-dependent systems. The design of heat-transfer equipment also depends on knowledge of rheological properties. Moreover, novel methods need to be devised for controlling the flow of concentrated two-phase systems.

Microbial cells immobilized on electrodes have decomposed glucose, producing hydrogen and a power output, albeit only 2.4 W/kg of dry immobilized cells. Research on biochemical fuel cells is encouraged, although commercial application in the near term is not likely.

1.2.2.3 Process Engineering Economic Evaluation

Any decision concerning the commercial feasibility of manufacturing a particular chemical from biomass, in competition with chemicals from nonrenewable resources, must be based on a market analysis and an awareness that final cost is to include sales cost as well as battery-limits production cost. Only the latter cost is addressed here.

Evaluation of process engineering systems is encouraged. This is perhaps best done by chemical and biochemical engineers with schooling in the use of optimal flow-sheeting, sparse matrix, and graphic interactive techniques. Process evaluation studies would permit distinguishing systems with economic potential. This type of discriminator function, based on conceptual designs, would be invaluable also in the identification of biotechnologically favorable basic research. Performance thresholds (in terms of yields and rates of production of chemicals) for process economic feasibility could be formulated.

Essential to these evaluations is the collection of sound, quantitative kinetic information on the biotechnological processes being considered. Well-controlled experiments on the selected organisms will generate preliminary data. Also, chemical engineering data banks should be scrutinized worldwide and access gained to those data banks having biotechnological information relating to biomass conversion.

1.2.2.4. Hybrid Processes

Some near-term advantages could accrue from hybrid operations of thermal conversion and biological conversion of biomass. Chemicals produced by thermal processing could be transformed biologically to other products and vice versa. A few examples are: (1) thermal conversion of lignin residue obtained from bioconversion of lignocellulose; (2) anaerobic fermentation of biomass gasification products (CO, CO_2, and H_2) to produce methane; (3) pyrolysis of biomass to produce levoglucosan, which can be converted by a mild hydrolysis to fermentable glucose; (4) biological conversion of gasifier product methane to methanol; (5) thermal processing of biomass to produce organic acids which could be converted biologically to methane; and (6) linkage of thermoelectric and bioconversion processes.

Process links with other energy technologies are possible also, but discussion of this is outside the scope of this summary.

1.3 A BIOTECHNOLOGICAL RENAISSANCE

By developing genetic engineering methodology and biochemical engineering, with the aim of establishing a biotechnology of biomass processing, industrial operations of considerable potential could emerge. Apart from the advantages of a "soft energy path," the potential for commercial exploitation of this approach to the production of fuels and chemical feedstocks may be like that which existed for the computer and microelectronics field several decades ago. Moreover, the technical advances would most likely diffuse to other areas of industry, such as the pharmaceuticals and food industry. A strong commitment by SERI/DOE to this very promising emerging field could not go amiss.

SECTION 2.0

SPECIFIC R&D RECOMMENDATIONS

2.1 INTRODUCTION

As the imported fraction of the U.S. oil supply grows, hydrocarbon costs are mounting. The market is beginning to motivate a search for substitute commodities. Interest is increasing in producing fuels and chemicals from biomass, with a consequent incentive to revive industrial microbiology.

In the 19th century Louis Pasteur showed that fermentation and putrefaction were caused by microbes. This discovery led to the development of industrial microbiology and the establishment of a thriving fermentation industry for producing chemicals. But cheap petroleum and a highly effective cracking technology for the production of solvents and other chemicals soon displaced microbiological industry, which subsequently focused more intensively on compounds not easily produced by chemical synthesis, such as antibiotics, enzymes, and vitamins. Emphasizing novel pharmaceuticals and aided by unprecedented developments in molecular biology, industrial microbiology further exploited the prodigious biosynthetic capabilities of lower organisms.

As the economic situation begins to favor again the fermentative production of industrial chemicals from carbohydrate sources, biotechnological industry is bound to be revived. Some of the old fermentation equipment has been dormant for a long time. For example, 500,000-gallon fermenters, with which acetone, butanol, and ethanol were produced, have been out of service for almost 30 years. This equipment was never very efficient, but R&D could bring it to a competitive level in the near term.

In the longer term, an efficient biotechnology must be designed and developed for processing biomass. The lead time for establishing a biotechnology of biomass processing will tend to be shorter than for other technologies of fuel and chemical production because biotechnological processing favors smaller-scale plants; the degree of biochemical engineering scale-up required is therefore reduced. In contrast, the capital intensity of coal-based chemistry favors large plants, even larger than plants now used for production of petrochemicals from oil.

In this section some specific organic chemicals considered to have potential as fuels and/or chemical feedstocks are discussed. The list is by no means exhaustive but it does cover major chemicals. Specific recommendations are made for R&D judged essential if biomass biotechnology is to be commercially feasible in the near future. The following organic chemicals are discussed:

- ethanol,
- methanol,
- methane and other chemical products of anaerobic fermentation,
- butanol and acetone,
- acetic acid,
- butanediol,
- glycerol,

- lactic acid,
- propionic acid,
- hydrocarbons and other petrochemical substitutes produced by microbes and plants, and
- lignin.

Specific R&D projects for ethanol production are listed in considerable detail. Similar R&D structures could be followed for other chemicals.

2.2 ETHANOL

Ethanol is considerably versatile in its uses as a fuel, a solvent, and a chemical feedstock. U.S. demand for this chemical in 1980 could exceed 220 million gallons. As a fuel, water-free ethanol has a Research Octane Number of 110; clearly it has a potential for use in internal combustion engines. (In fact, since 1977 the Sao Paulo telephone company has been operating a fleet of Volkswagens on straight ethanol with modified engines.) Ethanol ranks second only to water as the most widely used solvent in chemical industry for a large range of industrial products, including paints, dyes, lacquers, and oils. A host of chemical products, such as ethylene, butadiene, acetaldehyde, and acetic acid, are derived from this key initial chemical feedstock. Ethylene, normally produced from petroleum, is a prime chemical feedstock; major derivatives are polyethylene, ethylene oxide/glycol, vinyl chloride, and styrene.

The demand for ethylene reflects the economic strength of a large segment of the U.S. industry. The present demand for ethylene is more than 10 million tons/yr, but the supply is becoming tighter. The anticipated rise in price favors a biotechnological route for its production via ethanol.

Butadiene is generally produced as a coproduct from steam cracking of hydrocarbons in ethylene plants. About 1.8 million tons were produced in 1978 at a selling price of 20.5¢/lb. Its major derivatives are styrene-butadiene rubber, polybutadiene, and hexamethylene-diamine. Because butadiene is a coproduct, its supply varies with the supply of oil-derived ethylene. This disadvantage could be alleviated by synthesizing ethylene from fermentatively produced ethanol. Butadiene might also be synthesized from bacterially produced butanediol.

2.2.1 Ethanol Production From Biomass

For producing ethanol, a range of biomass feedstocks are available, including molasses, sugar cane juice, corn, grain, and sorghum. Waste products such as whey from the food industry and sulfite waste liquor from the paper pulp industry are potentially rich sources of fermentable sugars. For example, 1500 million pounds of lactose are produced from whey per annum in the United States; the potential yield of ethanol is approximately 100 million gallons. Except for the waste materials, the cost of these feedstocks is high—up to 75% of the total production cost—but the biotechnology for their processing is established.

Another class of feedstock is cellulosic and hemicellulosic substrate from, for example, wood, waste paper, and corn stover. This substrate is not expensive and is available in large amounts, but the cost of conversion to fermentable sugars is considerable.

In a process economic evaluation of the production of ethanol from maize, the University of Pennsylvania/General Electric group estimated a production cost of $1.40/gal., without return on investment or byproduct credits. The cost of the feedstock at $2.50/bu represents 65% of the total cost. With a credit for distiller's dried grains, the net production cost is $1.23/gal.

Only two processes for cellulosic substrates have been operated successfully at a scale considerably larger than bench scale: the Schoeller/Madison acid hydrolysis process and the Gulf Oil/University of Arkansas simultaneous saccharification and fermentation process. The acid process is well-tried technology and was used during World War II. In the Soviet Union 30 plants are in operation. Recoveries are poor—at best, approximately 75% of the original amount of sugar. The Penn/G.E. group has estimated a production cost of $1.5 to $2.0/gal. of ethanol.

The Gulf Oil/University of Arkansas process has been used for converting wood polysaccharides into ethanol at a rate of 1 ton of feedstock per day. Cellulose conversion is accomplished by using a mutant strain of Trichoderma reesei to produce a cellulase multienzyme system. Sugars from the hydrolysis are converted by a mixed culture of yeasts. The simultaneous hydrolysis and fermentation eliminates glucose inhibition. The pretreated slurry contains 7.5% to 15% cellulose. Ethanol is recovered by steam-stripping and rectification. Residue combustion could provide thermal energy and motive power to operate a plant. A commercial facility processing 1000 tons of cellulose feedstock per day is estimated to cost $70 million and yield 250 tons ethanol/day (about 25 million gal./yr). The production cost is estimated to be $1.16/gal. By-product molasses can be used for animal feed. If a plant is designated a waste conversion facility, municipal bond financing is possible. How far the process design and operation is from optimum cannot be judged at present, but it is very promising. It would be of interest to evaluate the economics of the process at a considerably lower throughput of, for example, 100 tons/day.

2.2.2 Recommended R&D

Two directions for R&D are recommended:

- A short lead-time effort to bring conventional fermentation technology to a more efficient level; and
- A longer lead-time effort to develop a new biotechnology for processing biomass.

2.2.2.1 Recommendations for Improvement of Conventional Fermentation Technology

- Improve the efficiency of ethanol recovery. This is called the "Btu problem." A fresh look must be taken at conventional chemical engineering unit operations. It is necessary to redesign conventional distillation columns so that they operate with smaller changes in entropy. Heat pumps and other thermal conservation devices must be investigated. Work on novel separations processes (for example, membrane separation, adsorption, crystallization) should be pursued actively.

- Promote the utilization of easily fermentable wastes. For example, lactose waste from the food industry could be fermented to produce about 100 million gal./yr of ethanol. Paper-pulp industry waste is another possibility.
- Develop new yeast strains. The usual strains have little tolerance for high concentrations of ethanol. The development of new strains would make it feasible, from an engineering point of view, to introduce vacuum fermentation. Yeasts able to function at high temperatures could permit operation at greater rates. Strains that can function in high concentrations of carbohydrate are needed. Development of heterothallic strains would facilitate genetic manipulation.
- Develop continuous fermentation. Rates of throughput not limited by the maximum specific growth rate of the organism could be achieved by immobilizing yeast cells by using suitable flocculating strains or by imbedding cells in polymers (biocatalyst pellets).
- Investigate inexpensive engineering materials in conjunction with unconventional fermenter geometries. A prize could be offered by SERI/DOE for a low cost, workable (albeit unconventional) design of a fermentation plant.
- Develop on-line computer control and process optimization. This would involve formulating suitable algorithms and devising new instrumentation for carrying out optimal control strategy.
- Study the economic utilization of by-products, such as distillers' dried grains (DDG).
- Study the environmental impact of waste from biotechnological processing, including an assessment of water requirements.

2.2.2.2 Recommendations for the Development of a New Biotechnology of Biomass Processing

- Weigh the relative merits of various pretreatment processes for lignocellulose, including comparison of enzymic methods with chemical methods. For example, examination of the effects of redox catalysts could be worthwhile. The thermodynamic efficiency of exploding wood with steam pressure (Iotech process) should be determined. A comprehensive economic evaluation of pretreatment techniques (biotechnological, chemical, and physical), based on sound experimental results, is needed.
- Develop microbial strains for hydrolyzing cellulose and hemicellulose.
- Improve techniques for selecting strains of microorganisms that produce large quantities of cellulases.
- Set up standard procedures for the preparation of cellulose and hemicellulose so that experimental comparisons can be precise.
- Extend the number of species of cellulolytic microorganisms being investigated.
- Study the molecular mechanisms of cellulase production and action. Stabilization and activation are important requirements for process efficiency.
- Elucidate the mechanism of action of xylanases. Efficient ways of converting hemicellulose to ethanol need to be developed. Hemicellulose comprises about 25% by weight of lignocellulosic biomass.

- Investigate more fully the biochemistry and genetics of phytopathogenic fungi; for example, the isoenzymes of cell-wall-degrading enzymes. How mechanisms of phytopathogenicity involve extrachromosomal elements (plasmids) requires elucidation.
- Determine at which stage of development biomass should be harvested for a maximum production of fermentable sugars. At an early vegetable stage there would be less lignification.
- Assess unconventional crops of high photosynthetic efficiency in regard to their suitability in a biomass production/conversion system. Crops should be screened on the basis of their hydrolyzability as well as their photosynthetic efficiency. Already in the Philippines nitrogen-fixing Leucaena is used as an energy crop. Weeds (for example, the common thistle) require evaluation. Information accumulated regarding biological control of undesirable plants (using fungi, for example) would be useful. It is recommended that SERI/DOE support a program using standardized experimental procedures with the aim of producing a biomass handbook. Precise quantitative information on not only biomass production efficiency but also on the bioconversion potential of various plant species could be included in such a handbook.
- Investigate the transfer of genes for growth at high temperature from obligate thermophiles (for example, B. caldolyticus) to mesophiles of biotechnological merit. The genetic control of thermophily needs to be understood.
- Study the role of cyclic nucleotides in catabolite repression. Biochemical manipulation, as an alternative to genetic methods, might be used to achieve catabolite repression resistance.
- Investigate and optimize novel fermenter geometries, including immobilized-cell bioreactors. Study microbial attachment to solid surfaces. Work is needed on cell-surface chemical topography.
- Direct biosynthetic pathways toward a homofermentative mode for increasing yield of a desired product. Considerable support for work on microbial physiology would be required.
- Investigate microbiological and chemical engineering aspects of mixed-culture processing, including possibilities with photosynthetic bacteria.
- Construct hybrid microbial strains for metabolizing pentoses as well as hexoses.
- Investigate respiration-deficient strains of yeast for increased production of ethanol.
- Extend work on membrane biochemistry in relation to ethanol- and thermotolerance.
- Develop a chemical engineering methodology for novel bioreactors to accomodate insoluble substrates.
- Examine preferred substrates (the polyauxie phenomenon) for mixtures of sugars from biomass hydrolysis.
- Study quantitatively the rheological behavior of cellulosic slurries in high concentration. Develop mathematical models.
- Set up and maintain a bank of cultures and plasmids important to biotechnological processing of biomass.

Decisions will have to be made as to which avenues of R&D should be emphasized. This is not an easy task. Hasty action founded on inadequate information could be detrimental to the progress of a biotechnological energy development program. For example, the question could arise whether to pursue mixed-culture processing or microbial hybrid construction. Mixed-culture processing poses engineering problems in bioreactor design, control, and stability. In the construction of hybrids, however, there is no guarantee of compatability in experiments on gene transposition. It is therefore advisable to exert a resonably high level of R&D effort in both directions until solid ground for discrimination is gained.

The type of biotechnological R&D program recommended here for ethanol production applies to other chemical products. Such a program provides a diversified but sound technical base for establishing a biotechnology of biomass processing. Thus, a renewable resources chemicals industry and, moreover, an attractive option in the energy market could be developed.

2.3 METHANOL

At present, thermal conversion processes are being explored for the production of methanol from biomass. A biotechnological process for methanol production does not yet exist, but two possible approaches are:

- To produce methane from biomass by anaerobic digestion and convert methane to methanol using methylotrophs (methane-oxidizing microorganisms); and
- To produce methanol as a secondary metabolite in methanogenesis.

The following R&D is recommended:

- Select and develop methylotroph strains.
- Attempt biochemical blocking so that methanol accumulates.
- Induce genetic blocks using chemical mutagens.
- Attempt, by genetic engineering, to transpose a methanol-producing capability to a fast-growing host.

A biotechnological process for methanol production cannot be fully developed in the near term, but, because methanol is important as a liquid fuel, it is worth pursuing. Moreover, methanol can be converted readily to olefins and aromatics using zeolite catalysts (Mobil method).

A feature of some species of methylotrophic bacteria is the ability to perform cooxidations in which hydrocarbons other than methane are converted to various chemical products. For example, alkenes can be epoxidated and alkanes converted to methyl ketones. This could have considerable biotechnological potential.

2.4 METHANE AND OTHER CHEMICAL PRODUCTS FROM ANAEROBIC FERMENTATION

Methane is already produced on a large scale by anaerobic fermentation of biomass, but the process is not efficient. Greater yields and lower retention times are necessary.

The biochemistry and physiology of anaerobic conversions of biomass to methane and other chemicals need more study. For example, the mechanism and bioenergetics of acetate formation by anaerobic species are poorly understood. It is crucially important to build up genetic information on methanogens.

The following R&D is recommended:

- Study microbial ecology of anaerobic processes and investigate interspecies hydrogen transfer. Little is known about the interactions among fermentative, acetogenic, and methanogenic species.
- Investigate possibilities for using genetic techniques to accelerate methane production; there is a pressing need for genetic information on methanogens.
- Attempt to increase yields by suitable pretreatment.
- Investigate the feasibility of producing chemical feedstocks such as acetic acid and propionic acid.
- Examine the possibility of developing a continuous feed for anaerobic digestion plants. Currently, feedstock is added intermittently and could contribute to process instabilities.
- Study the application of on-line computer data logging, analysis, and control.
- Obtain quantitative data on the use of marine inocula for digesting macroalgae.
- Develop thermophilic strains of anaerobes.
- Examine strains of methanogens for oxygen tolerance.

2.5 OTHER CHEMICAL FEEDSTOCKS (OR FUELS) WITH POTENTIAL FOR BIOTECHNOLOGICAL PRODUCTION

A few selected chemicals are discussed here. Some might soon present an economic challenge to fossil fuels. Chemicals produced from transforming biomass biologically could be the basis for a renewable resources plastics industry.

Similar to the program recommended for biotechnological production of ethanol, an R&D program could be structured efficaciously within two time-frames:

- A near-term effort in which conventional fermentation (for making butanol and acetone, for example) is resuscitated and improved; and
- A longer-term development of new biotechnological processing.

Moreover, a thorough chemical engineering economic evaluation of biotechnological processes for manufacturing chemical feedstocks is lacking and should be performed very soon. Such studies, which should include precise energy and mass balances, could use quantitative data possibly available from the plants operated several decades ago, but new data would be needed also. Market analyses and sales forecasts could be done in conjunction with process economic evaluations.

2.5.1 Butanol and Acetone

Butanol and acetone are widely used in industry, notably as solvents. About one quarter of a million tons of butanol and 1 million tons of acetone at 24¢/lb and 19¢/lb, respectively, are produced each year in the United States. Acetone is currently produced by the cumene hydroperoxide process, while butanol is synthesized using the Oxo and Aldol processes.

Before 1952, when fermentation butanol and acetone were produced in the United States, C. acetobutylicum was used. Initially, potato starch was the feedstock; it was later replaced by molasses. Competition with chemical synthesis would increase considerably if cheaper feedstocks were available. Solvent ratios of 60% butanol, 30% acetone, and 10% ethanol are obtained from starch; and 68% butanol, 30% acetone, and 2% ethanol are obtained from molasses. Product recovery is difficult because of low concentrations (2.5% mixed solvents). Contaminants and stillage disposal are problems.

Because yields are low, fermentative production costs of these solvents are very sensitive to feedstock and energy costs. In a preliminary economic study, Humphrey and Nolan (see Vol. II of this report) estimated production costs of solvents (acetone, butanol, and ethanol) from corn and molasses to be 19¢/lb and 16¢/lb, respectively. Lenz and Moreira (see Vol. II of this report), using a detailed economic analysis, concluded that feedstock cost is more than 60% of the cost of production and that the economic incentive for molasses-based fermentation, compared to chemical synthesis, is marginal.

The economic incentive is good for fermentation of whey waste, using C. acetobutylicum, because the cost of feedstock is low. Waste lactose could provide 30,000 and 15,000 tons/yr of butanol and acetone, respectively. The present annual demand is for 215,000 tons of butanol and about 1 million tons of acetone.

Methods of stabilizing the bacterial strains toward product solvents should be investigated. C. acetobutylicum is easily contaminated by bacteriophages; there is a need to develop an immune strain that will give a reasonable yield of solvents.

2.5.2 Acetic Acid

Acetic acid is chemically synthesized by oxidizing acetaldehyde or by reacting methanol with carbon monoxide. Production in the United States is almost 4 million tons/yr and the price is 18¢/lb.

Efficient biotechnological production of acetic acid is not yet near realization. Another method is to link biological processing and chemical synthesis. For example, production of ethanol by fermentation might be followed by chemical dehydrogenation to give acetaldehyde, which then could be oxidized to acetic acid.

The ancient process of fermenting ethanol to acetic acid could be revived and improved for large-scale application (1) by using an immobilized-cell bioreactor in continuous, rather than semi-batch, operation; and (2) by designing improved product recovery facilities. The high conversion efficiency of both hexose and pentose using the thermophilic anaerobe C. thermoaceticum merits further investigation. Yet another possibility is to select a mixed population of microorganisms able to ferment biomass anaerobically and produce acetic, propionic, and butyric acids. A suitable biochemical engineering design would allow maintenance of these populations and control of a continuous multistage

fermentation. Research on construction materials for fermenters is particularly important because of the highly acidic conditions.

2.5.3 Butanediol

Butanediol is an important chemical feedstock and development of biotechnological production could be worthwhile. Butadiene and methyl ethyl ketone (MEK) are produced from 2,3-butanediol. Production of MEK in the United States is about one quarter of a million tons/yr while that of butadiene is almost 2 million tons/yr, at prices of 20¢/lb and 20.5¢/lb, respectively.

During World War II, when countries were cut off from supplies of natural rubber, much research was performed on processes for producing butanediol. Butanediol can be produced by a variety of microorganisms at a cost of about $3.80/lb. Bacterial butanediol producers fall into three general groups according to the fate of the extra reducing power arising during glucose breakdown: (1) the butanediol-formate reaction in Serratia, (2) the butanediol-hydrogen reaction in Klebsiella, and (3) the butanediol-glycerol fermentation in B. subtilis. A. aerogenes is a good producer of butanediol and yields a mixture of stereoisomers. B. polymyxa ferments grain mashes, glucose, xylose, mannitol, and other carbohydrates to form butanediol. Bacteria could be used for converting cellulose and hemicellulose hydrolysis products; wastes from the food and paper pulp industries are also worth consideration. Recovery of butanediol is difficult because of its high boiling point (180°C) and high solubility in water.

Some yeasts can form acetylmethylcarbinol, which is readily converted to butanediol using 2,3-butanediol dehydrogenase.

Extensive pilot plant work on butanediol products from molasses was done before 1952 at the Canadian National Research Laboratories. They estimated a total operating cost of 26¢/lb (return on investment not included). As prices of chemically synthesized butadiene and MEK increase, the biotechnological production of butanediol will come into its own.

2.5.4 Glycerol

Glycerol has a host of industrial uses as a commodity chemical and feedstock, and its potential as a component of auto diesel oil merits investigation. About 100,000 tons/yr are produced in the United States from propylene or propane or by the saponification of fats and oils.

Osmophilic yeasts might be used for the biotechnological production of glycerol. The yeasts grow well in the presence of high concentrations of carbohydrate, producing a variety of polyhydric alcohols. The fermentation process is a conventional technology, but product recovery is difficult. An alternative source of production is the salt-tolerant alga Dunaliella.

2.5.5 Lactic Acid

Lactic acid is a feedstock for the production of compounds such as acrylic acid and propionic acid. A large variety of carbohydrates can be fermented by Lactobacillus and the

fermentations are homolactic. L. pentoaceticus ferments xylose to lactic and acetic acids. The current prices of lactic, acrylic, and propionic acids are about 68¢/lb, 40¢/lb, and 20.5¢/lb, respectively. U.S. production of acrylic acid and propionic acids is about 100,000 tons/yr and 40,000 tons/yr, respectively.

2.5.6 Propionic Acid

Chemically synthesized by propionaldehyde oxidation, about 50,000 tons of propionic acid are annually produced in the United States at a price of 20¢/lb. It is used chiefly as an intermediate in plastics manufacture and as a preservative.

Propioni bacterium arabinosum ferments wood sugars to propionic and acetic acids at a ratio of two to one. This process could become commercially viable; cellulose propionate has a well-established demand. Product tolerance and homofermentatively directed strains should be investigated.

Propionic acid might also be produced by a mixed bacterial population during anaerobic fermentation of biomass in a continuous fermentation process (see Section 2.5.2).

2.6 MICROBIAL AND PLANT PRODUCTION OF HYDROCARBONS AND OTHER PETROCHEMICAL SUBSTITUTES

The potential for biotechnological production of fuels and commodity chemicals by microorganisms and plants is not limited to fermentative processes. A capability for synthesizing oily hydrocarbons is found in both microbial and plant species. Large quantities of terpenes are produced by some fungi. Certain pathogens have an active cellulase system and also produce ethylene at low rates (e.g., Fusarium).

Algal species such as Botryococcus synthesize high concentrations of hydrocarbons from fatty acids. Squalenes and hydrosqualenes are synthesized by the extremely halophilic organism Halobacterium. The amounts of various polyisoprenoid components in cultures can be varied by altering aeration rates. The isolation and study of microorganisms from extreme environments (such as polar regions and saline environments) could have a technological payoff. The oil-producing capabilities of certain arid-zone plants (such as Euphorbia) have been known for a long time. The marine environment, wherein lie rich possibilities for harnessing planktonic biosynthetic activity, is an untouched field except for active interest being demonstrated by pharmaceutical companies.

The following R&D is recommended:

- Screen organisms to identify those producing chemicals of commercial interest.
- Evaluate the chemicals as potential fuels and/or chemical feedstocks.
- Measure rates of metabolite production.
- Investigate the physiology of the organisms and methods of increasing yields of biomass.
- Perform a preliminary process economic evaluation and establish thresholds of economic feasibility.

- Analyze biosynthetic pathways and their regulation. Identify enzymes and manipulate pathways.
- Evaluate the possible conversion of metabolites by microbial or synthetic means to commercially attractive compounds.
- Perform genetic analysis.
- Apply genetic engineering technology to enhance rates of production or to couple biosynthetic features.
- Perform chemical engineering conceptual flow-sheeting.
- Initiate biochemical engineering design and development.

It is important to keep an open mind about what could constitute a suitable fuel and/or chemical feedstock. For example, scrutiny of the squalene structure reveals a possibility for pterephthalic acid production. (Petrochemical-based U.S. production of pterephthalic acid is about 2 million tons/yr.)

2.7 LIGNIN

Lignin is a phenylpropanoid structural polymer of vascular plants which gives rigidity and binds cells. Other than cellulose, lignin is the most common organic compound cycled in the biosphere, and its biotechnological possibilities should be developed.

Lignin can be used (1) as is, (2) chemically modified, or (3) after degrading to chemical feedstocks and/or fuels. The third use is addressed here. Vanillin, dimethyl sulfide, and methyl mercaptan are produced commercially from lignin. Examination of lignin structure suggests various possibilities for production of chemicals, including ethylene, acetic acid, methanol, methane, acetylene, phenol, catechol, cresol, xylenol, benzene, and carbon monoxide.

Chemical processing of lignin has a rather tenuous economic incentive when compared to petrochemical routes for lignin products. Reaction conditions are severe, and yields of the complex range of products are not easily controlled.

The biological conversion of lignin is attractive because of its advantages of specificity of action, but the development of a lignin bioconversion process in the near term is not possible. Degradation and utilization of lignin by microorganisms is being researched in the United States and Europe. The rates of conversion, however, are extremely slow.

About 1 million tons/yr of phenol are produced in the United States. The selling price is 24.5¢/lb, a price level which has tripled over 15 years. Annual U.S. production of benzene is about 1.5 billion gal. at a price of 90¢/gal. Thus, economic incentive is emerging for producing phenol and benzene from biomass.

The following R&D is recommended:

- Set up a standard procedure for lignin preparation so that experimental results can be compared.
- Perform a process evaluation study to select the best procedure for isolating lignin.

- Identify the most promising microorganisms for lignin conversion.
- Produce reliable quantitative kinetic data from controlled experiments.
- Perform chemical engineering flow-sheeting analyses and establish thresholds for process economic feasibility.
- Develop and genetically engineer strains of promising microbial species.
- Elucidate the enzymic mechanisms of lignin conversion.
- Study the biogenesis of lignin. Investigate biochemical or genetic interruption of biosynthesis, with the objective of producing commercially attractive intermediates.
- Develop biotechnological processing of Kraft wastes from the paper-pulp industry.

SECTION 3.0

DESIGN AND MANAGEMENT OF A NATIONAL R&D PROGRAM TO ESTABLISH A BIOTECHNOLOGY OF BIOMASS PROCESSING

Biotechnological processing, a renewable resources industry, could soon be an economically feasible means of chemicals manufacture. It is crucial for the national program to support this potential. Confidence can be stimulated by the imminent revival of a reasonably well-tried technology, improved by new and sophisticated R&D methodology.

The overall objective recommended in this survey is to establish a Biotechnology of Biomass Processing and thus to support and accelerate the design of efficient commercial-scale operations. The R&D structure embraces a richly diversified field ranging from molecular genetics research to biochemical engineering design. It is recommended that biotechnological R&D strategy be organized as an integrated set of the following three disciplines:

- Biochemical Engineering,
- Microbial Genetics, and
- Biochemistry.

Basic and applied research, theoretical and experimental, would be conducted in all three disciplines. The biochemical engineering group would perform process economic evaluations and exercise a discriminatory function in determining process goals and hence influence the overall R&D planning of the other groups. Another responsibility of the engineers would be to generate design information, using mathematical modeling and bench- and pilot-scale work, for constructing Process Demonstration Units (see Section 4.0). The process economic evaluations and designs would depend heavily on the experimental information produced by the genetics and biochemistry groups. This type of integrated, biotechnological R&D is being set up at the Solar Energy Research Institute in Golden, Colorado.

Work in these three disciplines could be carried out by one contractor, or be distributed among several contractors, depending on the skills available. In any event, managerial skill would be required to orchestrate the program. This involves thorough technical grasp of the activities of the contractors, the ability to discriminate between good and poor ideas, and the insight to distinguish productivity from mere report production.

To facilitate management of the national program, it is recommended that the contractual work be arranged under the following categories:

- Microbiological Research and Development;
- Biotechnological Process Evaluation, Control, and Optimization;
- Biotechnological Process Development and Demonstration; and
- Design and Development of Separations Processes.

These four categories would be grouped under the overall title: Biotechnology of Biomass Processing.


SERI

SECTION 4.0

COMMISSIONING AND IMPROVING EXISTING BIOTECHNOLOGICAL FACILITIES:

A RECOMMENDATION TO SERI/DOE

As the scarcity and price of a commodity increase, market forces encourage the seeking of substitutes. Product substutution is the lifeblood of the chemical industry. At present, a dwindling supply of crude oil, coupled with an undiminished demand for fuels and chemical feedstocks, compels consideration of alternative renewable resources such as biomass. The commercial imperative for R&D on bioconversion of biomass is to produce fuels and chemicals as efficiently as possible. This goal can be achieved by developing suitable biotechnological processes.

Several decades ago, biotechnological processing of commodity chemicals from fermentable substrates was a robust commercial activity. The economic challenge of cheap petroleum could not be met, however, and the fermentation plants were shut down. Fermentation butanol and acetone have not been produced in the United States for almost 30 years. In general, the equipment is dormant or used for storage purposes, but the fermentation capacity is considerable. (Since 1976 more than 50 breweries have been shut down in the United States.) To contribute to the momentum of the impending biotechnological renaissance, it is recommended that a plan be formulated as soon as possible for resuscitating dormant fermentation plants and that these plants be rendered efficient by an appropriate injection of R&D, as discussed in Section 2.0

In order to help industrial manufacturers bring their former fermentation operations to commercial readiness, SERI/DOE could set up a cooperative program. Biotechnological consultation could be offered to the manufacturers to improve the efficiency of their plants. Process engineering data probably can be found in operational logbooks. With these records, former operating conditions could be reviewed and process conditions planned. From accounting archives, equipment and other costs could be gleaned. Such information on costs, brought up to date, could be used for process economic evaluation. No recent studies of this kind exist for fermentation processes.

Basically, some of these plants could serve as ready-made Process Demonstration Units, following, perhaps, some modest expenditures. A joint team of company and SERI/DOE engineers could obtain valuable process data from preliminary runs. This demonstration scale of operation could reveal problems unperceived on the small, laboratory scale. Suitable R&D might be pursued on a cooperative basis by SERI/DOE and the private companies.

This collaboration could provide fairly soon the momentum needed for a revival and improvement of the fermentation industry. Moreover, such effort undoubtedly would stimulate development of a new biotechnology for producing commodity chemicals and fuels based on the renewable resource, biomass.

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