General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

JPL Publication 83-58

DOE/CS-66001-1
Distribution Categories
UC-61a & UC-61d

ECUT
ENERGY CONVERSION AND UTILIZATION TECHNOLOGIES PROGRAM

Chemical Processes Project Annual Report FY 1982

Compiled by
R.E. Wilcox

July 1, 1983

Sponsored by:
Energy Conversion and Utilization Technologies Division
Office of Energy Systems Research
U.S. Department of Energy

Through an Agreement with
National Aeronautics and Space Administration

Prepared by:
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91109

JPL Publication 83-58

DOE/CS-66001-1
Distribution Categories
UC-61a & UC-61d

ECUT
ENERGY CONVERSION AND UTILIZATION TECHNOLOGIES PROGRAM

Chemical Processes Project Annual Report FY 1982

Compiled by
R.E. Wilcox

July 1, 1983

Sponsored by:
Energy Conversion and Utilization Technologies Division
Office of Energy Systems Research
U.S. Department of Energy

Through an Agreement with
National Aeronautics and Space Administration

Prepared by:
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91109

The Biocatalysis Research Activity is managed by the Jet Propulsion Laboratory, California Institute of Technology, for the United States Department of Energy through an agreement with the National Aeronautics and Space Administration (NASA Task RE-152, Amendment 307; DOE Interagency Agreement DE-AI01-81CS66001).

The Biocatalysis Research Activity focuses on resolving the major technical barriers that impede the potential use of biologically-facilitated continuous chemical production processes.

ABSTRACT

This is the FY 1982 Annual Report for the Chemical Processes Project of the U.S. Department of Energy (DOE), Energy Conversion and Utilization Technologies (ECUT) Program. The Annual Report presents the FY 1982 activities and accomplishments of the Chemical Processes Project. Additionally, it describes the FY 1983 planned research efforts and reorganization of the Project as the Biocatalysis Research Activity.

CONTENTS

CONTENTS (Cont'd)

Figure

Tables

EXECUTIVE SUMMARY

A. PROJECT DESCRIPTION

The Chemical Processes Project was one of six projects comprising the U.S. Department of Energy (DOE) Energy Conversion and Utilization Technologies (ECUT) Program during fiscal year 1982. The Project was established in May 1980 to investigate and develop new techniques and reaction sequences for the chemical processing industry. The California Institute of Technology's Jet Propulsion Laboratory (JPL) manages the Project for DOE.

In fiscal year 1982, the Project supported three major areas of research: Catalyst Modeling; Biocatalysis; and Separation. Catalyst Modeling research concentrates on developing models for predicting and optimizing the reactivity of major heterogeneous catalysts. Biocatalysis research focuses on resolving the major technical barriers that impede the potential use of biologically-facilitated continuous chemical production processes. Separation research focuses on establishing the technical feasibility of innovative, low energy intensive separation concepts.

In late 1982, the ECUT Program was reorganized. The Chemical Processes Project was consolidated and renamed the Biocatalysis Research Activity. In fiscal year 1983, Biocatalysis is the primary research focus. Catalyst Modeling activities, now called Molecular Modeling, are continued but focused on supporting Biocatalysis research.

B. GOAL AND OBJECTIVE

The current goal of the Biocatalysis Research Activity is to sufficiently build the technical and engineering base of biocatalysis technology to enable industry to displace a significant level of non-renewable resource requirements by 2000. The activity has an objective for each work element:

- Biocatalysis. Establish the technical feasibility for continuous production of chemicals using biocatalyzed processes by 1990.
- Molecular Modeling. Establish the technical feasibility for theoretically-based design, optimization, and control of biocatalyzed and hybrid chemically/biologically catalyzed chemical production processes by 1997.

C. FISCAL YEAR 1982 ACCOMPLISHMENTS OF THE CHEMICAL PROCESSES PROJECT

The Chemical Processes Project's activities during fiscal year 1982 were organized into the Catalysis and Separation work elements and a supporting planning function. Non-technical descriptions of these activities are presented here in the Executive Summary. Technical discussions are presented in Section II of this report. A glossary of key terms and concepts is provided at the end of the Executive Summary.

1. Catalyst Modeling

Catalyst Modeling research activities encompassed four research activities: Microscopic Reaction Models for Catalytic Processes; Electrocatalysis; Decarboxylation; and Ammonia Synthesis.

a. Microscopic Reaction Models for Catalytic Processes. Catalysts are widely used in industry to enhance the yield of a specific product from a chemical process. Commonly, a catalyzed process will also reduce the energy requirement over the non-catalyzed reaction conditions. However, the control which catalysts theoretically could provide to chemical processes is rarely achieved. This is particularly true in heterogeneous catalyst cases which comprise the majority of systems in use today. The short-fall in catalyst performance is due to the limited understanding of how catalysts actually function on a molecular basis. The sequence in which the supported catalyst participates in a chemical reaction involves catalyst-reactant, catalyst-intermediate, catalyst-product, catalyst-support and catalyst-catalyst interactions in a multitude of ways.

To optimize these catalyst systems, a more detailed understanding of catalysts must be developed on the molecular level. While this has long been the goal of researchers in industry and academia, the recent advances in theoretical chemistry and in translating these molecular level theories into computer programs now provides a much needed tool to assist in unraveling the role of catalysts. This combination of chemical theory guided by empirical observations to construct computer models is being applied to a specific catalytic reaction. The early postulates on catalyst performance have been verified by some experimental work reported by others in the literature. In addition, calculations on various possible catalyst-produced reaction intermediates have shown that specific reaction pathways can be predicted. This means that through calculations which can be manipulated by a computer, a description of resultant products can be made as a function of well-defined catalyst parameters. In this computer model the most probable sequence of chemical reaction, and intermediate chemical species associated with the sequence, can be identified. These calculations were based on parameters (e.g., chemical bond strengths, angles, and force fields) developed for the computer catalyst model.

Success with a specific catalyst and reaction by such a simple model is encouraging. This means that a prediction of reactive intermediates and resultant products may be feasible by a simple computer model using well-defined catalyst parameters. This is a necessary first-step in modeling catalyst systems to subsequently enable industry to design, formulate, prepare and utilize catalysts in more efficient and productive chemical processes.

b. Electrocatalysis. Most conventional industrial chemical processes, in order to attain acceptable reaction rates, are usually carried out at high temperatures and pressures, and therefore are energy intensive. Electrochemical processes (i.e., processes that use electricity to drive chemical reactions) are usually more energy efficient than conventional processes because they do not require high pressures and temperatures.

Electrocatalysis involves raising the energy efficiency of electrochemical processes by adding a catalyst to surfaces (i.e., electrodes) where chemical reactions occur. Certain forms of electrocatalysis offer the potential for an inexhaustible source of fuels (e.g., hydrogen from water, or higher hydrocarbons from simpler compounds--perhaps even carbon dioxide).

This research activity focuses on high potential electrocatalytic systems. During fiscal year 1982, the major technological areas where electrocatalysis could have a significant impact on energy savings were identified (e.g., chlorine synthesis and aluminum production). Also, a new compound was discovered for catalyzing water hydrolysis (i.e., the dissolution of water into oxygen and hydrogen).

c. Decarboxylation. Dilute streams of organic acids are byproducts of fermentation processes, paper and pulp industry waste streams, and processed urban waste. Currently, these are dumped because no economical method exists to extract the acids unless the streams are first concentrated. A catalytic process which would convert these dilute acids to useful chemicals such as alcohols and hydrocarbons may make feasible their recovery as a high-volume non-fossil feedstock. The catalyst should be able to cause loss of carbon dioxide from these dilute acids without having to heat the dilute solution and convert the acids to hydrocarbons that are not soluble in water and, therefore, can be separated at high energy efficiency. A rhodium-based catalyst was prepared and preliminary experiments were completed in which the catalyst appeared to decarboxylate (e.g., eliminate carbon dioxide from the acid compound) dilute acids. Electron spin resonance spectroscopy was used to characterize the catalyst as a first step leading toward the design of a model catalyst. Also, a hybrid chemical/biological process for the production of hydrocarbons was assessed.

The development of highly efficient decarboxylation catalysts will have two important impacts:

- They may make it economically feasible to recover up to 10^{13} Btu per year of hydrocarbons from dilute waste streams.

- They may be used to convert acids made by a biocatalyzed process to hydrocarbons, so that hydrocarbons for fuel or chemicals could be produced at substantially higher efficiency from renewable biomass feedstocks than from non-renewable fossil-based feedstocks.

d. Ammonia Synthesis. The potential energy savings of improving the conversion efficiency of synthesis catalysts in ammonia production was calculated. Three scenarios were examined that used varying degrees of catalyst improvement, reflected as lower temperature of operation.

It was determined that retrofit installation of new, improved catalysts would result in significant energy savings. Application of such catalyst systems (if they could be designed) and new technology could result in a 30% increase in thermal efficiency for production of synthesis gas and ammonia. Because synthesis gas is widely used for production of many chemicals

(including ammonia) and can be made from coal or biomass as well as from petroleum products, such catalysts could result in major energy and capital cost savings in future chemical and synfuels industries.

2. Biocatalysis

The Biocatalysis work element comprised four research activities in fiscal year 1982: Techniques for Plasmid Monitoring; Kinetics for Process Design; Cellulase Hyperproduction; and Membrane Fouling.

a. Techniques for Plasmid Monitoring. With the advent of recombinant DNA technology, it became possible, in principle, to make microorganisms produce enzymes (biocatalysts) and other desired products on demand. This is accomplished by introducing a small ring of genetic "instructions" called a plasmid into the microorganism. Unfortunately, when the cell divides it may lose some or all of these plasmids and, therefore, lose its "recombinant traits" (i.e., its ability to make the desired product). Because of this, laboratory researchers and, even more importantly, biochemical process engineers will require a technique whereby a large number of cells can be monitored individually for the existence and level of recombinant traits.

During fiscal year 1982, such a technique was developed. A flourogenic substrate that only yeast with the desired recombinant trait can process is added to the culture of growing yeast. The flourescent light emitted by individual cells is measured as the cells flow past a detector. The degree of flourescence produced by the product resulting from the recombinant cell's catalytic activity reflects the relative level of the desired recombinant trait. This technique allows the researcher to detail the number of recombinant individuals in large bacteria populations. This represents a significant step toward developing a method for monitoring the status of biocatalytic activity in industrial-scale continuous fermentation production processes.

b. Kinetics For Process Design. Analyses of the future of the chemical industry predict a major increase in the importance of biocatalysis because of the advent of recombinant DNA technology. This type of engineering will contribute significantly to future developments in biocatalysis by making currently rare enzymes available in large quantities and by enhancing the productivity of industrial microorganisms.

Among the technical barriers constraining development of genetically-engineered biocatalyzed chemical production processes is the lack of a quantitative description ("kinetic expressions") of the growth of recombinant cells and accumulation of their enzymes and metabolites. Synthesizing products that the cell has been genetically engineered to produce depends on a variety of substances within the cell. Conversely, the presence of the recombinant DNA (and possibly its resultant products) has deleterious effects upon the growth and functioning of the cell.

This research activity is working to describe these interactions at the molecular level, develop overall kinetic expressions useful for reactor

calculations, and determine optimal operating strategies for batch and continuous reactors utilizing recombinant microorganisms.

During fiscal year 1982, an initial model was formulated for predicting the impact of genetically engineered traits and cell regulatory techniques on the protein production levels of microorganisms. This effort focused initially on modeling an already well documented process--the production by the bacterium E. coli of an enzyme to digest lactose sugar--so that the model's predictions could easily be tested.

The model's predictions have coincided with experimental data spanning a wide range of cell environments and genetic backgrounds for E. coli. These results are encouraging and raise the prospects for defining models that will eventually be used to design optimal fermentation reactors and control strategies.

c. Cellulase Hyperproduction. The primary objective of this task is to identify and optimize species of fungi which produce and secrete high levels of the necessary enzymes collectively referred to as "complete cellulase," which completely catalyzes the decomposition of cellulose into glucose (a simple sugar that is the starting point for many chemical fermentations). This step is the main barrier to the efficient biological conversion of biomass into useful chemicals and fuels. It has been determined that over 50% of the cost in producing a fuel such as ethanol has been in the production of the glucose from the cellulose. This task will attempt to develop hyper-producers of the complete cellulase in fungi which have the unique property of excreting the enzymes. Such organisms would be able to inexpensively produce the complete cellulase in high yield, thereby reducing the overall bioconversion cost. The specific objectives of this work are the following: (1) select from a variety of candidates the best cellulase producers which are also easily genetically manipulated; (2) select mutants which constantly secrete cellulase; and (3) enhance the secretion by isolating hyper-secreting mutants.

To date, 18 strains of fungi have been screened. It has been confirmed that at least 2 genetically manipulable species produce cellulase at levels approximately 75% of the levels obtained by the best conventional species. Successful genetic modifications of the selected fungal species should result in cheaper sources of cellulase for use in bioconversion processes. This development could significantly improve the potential for biomass-based chemical production processes.

d. Membrane Fouling. Separation and purification of products, such as ethanol or butanol, from biocatalyzed fermentation processes consume most of the process energy required because the products are formed at low concentrations in water. For example, ethanol is formed at about 5 percent weight concentration and is distilled from the water to purify it. Separation by passing the alcohol through a thin plastic membrane that rejects water would increase the energy efficiency because no heating would be required. However, earlier experiments on fermentation products in water have indicated that

membrane fouling can decrease the rate of flow through the membrane and the selectivity of separation.

Therefore, previous work in this area was reviewed to provide a preliminary assessment of the potential of membranes for efficient separation of fermentation products.

Although development of a membrane process could decrease energy consumption in alcohol/water separations to less than half of that required by distillation, membrane purification of such fermentation products is relatively difficult (and expensive) because:

- The size of water and alcohol molecules is similar, therefore the sieve-like separation is not very selective; multiple separation steps would be needed.

- Fermentation water-product mixtures also contain the types of contaminants that contribute the most to fouling problems, such as organic slimes.

Therefore, membrane separation processes are not necessarily more energy-efficient or cost-effective than possible alternatives, and it will be necessary to make detailed energy/economic assessments of proposed separation alternatives followed by experimental validation to establish the most energy efficient, economically viable separation technology to be used for any specific fermentation process.

3. Separation

During fiscal year 1982, three research activities in advanced energy separation technology were undertaken to define specific areas for potential advancements in energy conservation: Second Law Analysis, Membrane Technology, and Critical Fluid Extraction.

a. Second Law Analysis. The Second Law Analysis determined that membrane processes consume most of their energy by forcing materials through membranes, and supercritical fluid extraction consumes most of its energy because of the need to increase and decrease pressure using large compressors. Also, analysis of a membrane process for separating oxygen from air indicated that energy consumption would be decreased to less than 60% of the energy needed for current commercial liquefaction processes.

b. Membrane Technology. The Membrane Technology activity identified a series of R&D areas where large improvements in energy efficiency could be obtained, including enhancement of permeation selectivity and flow rates through membranes.

c. Critical Fluid Extraction. In Critical Fluid Extraction, the solvent for dissolving the desired product and separating it from water or

other contaminants is above its critical temperature and pressure and acts as a very dense gas that reaches solution equilibrium very rapidly, i.e., it can dissolve and separate quickly and efficiently at moderate temperatures. For example, some brands of coffee are extracted with supercritical carbon dioxide to separate caffeine. Potential applications for significantly improved energy efficiency include separation of fermentation products from large amounts of water, and possible separation of useful products from tarsands or shale. Research areas identified include: determination of cosolvents to increase extract concentrations (to decrease energy per pound of product for each pressure-expansion cycle) and investigation of chemical reactions in supercritical solvents. Because the product is in a high pressure environment which tends to promote many chemical reactions, critical fluid extraction could be used to separate and react the product in a single step, with corresponding decreases in energy consumption.

4. Planning Support

Planning Support activities for the Project included the Guidance and Evaluation Panel, the Energy and Economic Analysis, Multi-Year Research Agenda, and the plan for a Separation Technology program.

a. Guidance and Review Panel. During fiscal year 1982, the Project formed a biocatalysis advisory group consisting of representatives from the chemical processing industry, genetic engineering firms, and universities. The Panel's charter encompasses advising the Project on the desirability of specific research activities and guiding research activities in progress.

b. Energy and Economic Analysis. This research activity has focused on developing and demonstrating an economic assessment methodology for comparing conventional and biocatalyzed chemical production processes. Initial modeling efforts have used a state-of-the-art fermentation process for acetone/butanol/ethanol (ABE). The objective has been to establish a candidate base case for comparison with new processes that will be developed as a result of research advances in biocatalysis. During fiscal year 1982, the initial base case model--a preliminary technical and economic evaluation of the ABE production process via fermentation--was completed.

c. Multi-Year Research Agenda. A major planning effort was undertaken in FY 1982 to develop a multi-year agenda for the Chemical Processes Project. The final report resulting from this activity describes the rationale, strategy, objectives, future activities, and resource requirements for biocatalysis, and catalyst modeling research.

d. Plan for Separation Technology Program. This activity, initiated and completed in fiscal year 1982, reviewed and integrated information in the vast and diverse field of separation technology. The

planning effort identified future areas of industrial significance for which energy-efficient separation techniques or methods should be developed.

D. FY 1983 PLAN FOR THE BIOCATALYSIS RESEARCH ACTIVITY

Research activities continuing from the FY 1982 Chemical Processes Project will be consolidated under the Biocatalysis and Molecular Modeling work elements of the Biocatalysis Research Activity.

1. Biocatalysis

Four of the research activities started previously will continue in FY 1983: Cellulase Hyperproduction; Kinetics for Process Design; Techniques for Plasmid Monitoring; and 2nd Law Analysis. New research activities during FY 1983 will include work on Chromosomal Amplification and one or two other research areas yet to be announced.

a. Chromosomal Amplification. The application of genetic engineering techniques in certain bacteria may lead to greatly reduced production costs for some organic chemicals. However, before this potential can be realized in large-scale industrial processes, a method must be developed for stabilizing and retaining genetically engineered traits (i.e., capabilities) in large quantities ("cultures") of bacteria.

A number of steps are required to genetically engineer a bacterium to yield a valuable product. First, the gene (instruction sequence) responsible for directing the bacterium to produce the protein of interest must be isolated and joined ("spliced") to the DNA of an appropriate plasmid. This plasmid is then introduced into a bacterium ("transformation") where the plasmid will multiply ("ampliflication") and a strain of bacteria will be established that carries multiple plasmid copies in each bacterial cell. The existence of the foreign gene in numerous plasmid copies results in higher yields of the desired product than if only a single or a few plasmid copies had the desired recombinant trait. Because bacteria can be grown on relatively inexpensive feedstocks (e.g., biomass), production costs for some organic chemicals may be significantly lower if genetically engineered processes can be cheaply scaled up.

One of the major technical barriers constraining such a production process arises from the typical characteristic of plasmids to float freely in bacterial cytoplasm, unconnected to the chromosome. Because only chromosomes, and not plasmids, consistently duplicate themselves before a bacterium physically divides and grows into two parts, the number of plasmid copies in each bacterium after division is not stable (i.e., the number may either increase or decrease). If the plasmid multiplies too much, it can overburden and kill the carrier bacterium; if it multiplies too little as the bacterium multiplies, the plasmid is lost. In fact, plasmid loss in scaled-up bacterial cultures appears to be a significant shortcoming of the general technique of plasmid splicing.

This research activity is testing the possibility of solving the plasmid stability problem by inserting the genetically engineered plasmid directly

into the bacterial chromosome and amplifying it (or just the foreign gene) in place. Because the plasmid with its foreign gene of interest would then be part of the bacterial chromosome, the desired recombinant trait could not be easily lost as the bacterium multiplies.

2. Molecular Modeling

The Electrocatalysis and Catalyst Modeling activities will continue in FY 1983; however, both efforts will stress research areas relevant to biocatalysis. The Electrocatalysis activity will focus on developing transition metal complexes as electrocatalysts for nitrogen fixation. The Catalyst Modeling effort will focus on examining biocatalytic and hybrid biologically/chemically catalyzed processes. No new research contracts in Molecular Modeling are planned in FY 1983.

3. Planning Support

The Guidance and Evaluation Panel will review and select research topics to be included in the Research Opportunity Notice (discussed below) and subsequent competitive solicitations. Also, the Panel will further develop the definitions of technical and economic issues relevant to biocatalyzed chemical production processes in the context of industrial interest and ECUT objectives.

The second phase of the Energy and Economic Analysis will begin. This effort will include an assessment of energy and economic impacts of expected generic research advances on fermentation process design and engineering.

New Planning Support activities include a solicitation of interest for industry, universities and research institutions to conduct research for the Biocatalysis Research Activity.

E. GLOSSARY

Bacteriophage - A type of virus that attacks bacteria rather than ordinary cells. A particle of bacteriophage consists of a nucleic acid (usually DNA) molecule enclosed in a protein shell. The nucletic acid can enter a bacterium and either multiply in it to form progeny particles, or variously interact with the chromosome of the bacterium.

Bacterium/Bacteria - The smallest unicellular microorganisms, usually enclosed in a hard cell wall. They do not have mitosis, the complicated mechanism of animal and plant cells for the equal ripartition of chromosomes at cell division. They have apparently only one chromosome. A great many bacterial types are known, performing an enormous variety of reactions. Most bacteria are free living; some are the cause of disease.

Biocatalysts - Catalysts, called enzymes, that are biological in origin and participate in the metabolic activity of cells.

Biomass - Any plant material: leaves, wood, bark, algae, etc.

Catalyst - Any substance that facilitates the occurrence of a chemical reaction. In the presence of the appropriate catalyst, reactions that would occur spontaneously only at very high temperatures can take place at room temperature.

Chemical or Chemical Product - Examples are alcohols, acetone, and acids. These are small molecules that may be used as solvents, fuels, or to make other chemicals or products such as plastics or rubber.

Chromosomes - The main cell structures that carry genetic information. The main component of a chromosome is a long DNA chain. A chromosome can be visualized as a string of genes. Animal and plant cells have several chromosomes (a constant number for each species) contained in the nucleus. In a bacterium, there is only one chromosome, free in the cytoplasm of the cell.

Cosolvent - A solvent added to a different solvent to increase the ability of the latter to dissolve a product, e.g., a chemical containing chlorine added to a hydrocarbon will dissolve dried paint better than the hydrocarbon alone.

Critical Fluid Extraction - See extract.

Critical Pressure - The pressure exerted by a chemical if it is confined in a small space at its critical temperature. For carbon dioxide it is about 1100 pounds per square inch.

Critical Temperature - The temperature (characteristic of each chemical) above which the chemical as a gas cannot be changed to a liquid by increasing the pressure. It is about 31°C for carbon dioxide.

Cytoplasm - The main body of a cell, exclusive of the nucleus (in a bacterium, exclusive of the chromosome) and of the cell membrane and wall.

DNA - Deoxyribonucleic acid: the type of nucletic acid of which chromosomes are made. As a molecule, it is a linear structure, consisting of a chain (or double chain) of four types of small molecules ("bases"). Different DNAs differ in the sequence of such bases, a bit like messages in Morse code. The length of a DNA molecule may be from a few thousand bases to millions.

Decarboxylation - A chemical reaction where a carboxylic acid, such as acetic acid, is converted to a hydrocarbon, such as methane, by loss of carbon dioxide. (Vinegar is essentially a dilute water solution of acetic acid prepared by a biocatalyzed process; methane is the major product in natural gas.)

Distillation - A process in which a chemical can be separated from water (or another chemical) by heating the mixture. The chemical that boils at the lowest temperature is converted to a gas or vapor first when that temperature is reached. The chemical is then cooled to convert it back to a liquid which contains less water or other chemical.

Electron Spin Resonance Spectroscopy - A sophisticated instrumental technique for measuring the number and types of certain sites on a material or catalyst where chemical changes can take place.

Element - In the chemical sense, the small components of molecules, such as carbon (symbol-C), hydrogen (H), oxygen (O), nitrogen (N), chlorine (Cl), sulfur (S), etc. The pure elements will have altogether different characteristics than the chemical products that are composed of them. For example, sodium (Na) is a liquid metal that reacts violently with chlorine, a yellowish, poisonous gas, to give sodium chloride, or table salt.

Enzyme - A protein acting as a catalyst for a particular chemical reaction.

Extract, Extraction - To separate a chemical product from water or contaminants by selectively dissolving it in a solvent. In critical fluid extraction, the solvent (usually carbon dioxide) is under pressure. When the pressure is released, the carbon dioxide (in the form of a gas) is no longer a good solvent for the product and can itself be separated by allowing it to diffuse away from the product.

Feedstock - Any relatively available substance that can be converted by chemical reactions to a more useful chemical product or products. At the present time the most common feedstocks for organic chemical production are petroleum and natural gas.

Feedstock Energy - The energy content of the feedstock; the energy available in Btu/lb that would be obtained if it was burned as a fuel.

Flourogenic Substance - A non-flourescent substance that can be processed into a flourescent product.

Gene - In general, a segment in a DNA molecule that specifies the sequence of amino acids in a type of protein. A mutation in a gene will cause the formation of an altered, often non-functional protein. Hereditary traits are determined by specific genes, usually through the proteins genes make, and the products (or "metabolites") of the reactions catalyzed by such proteins.

Heterogeneous Catalyst - An inorganic catalyst positioned on a support material which is not miscible in the reacting medium.

Intermediate - Molecular species that is in a transition between initial reactant molecules and the subsequent product species.

Membrane - A thin solid film or sheet, usually plastic, which is designed to let some chemicals (or water) pass through it by a sieving action while retaining other chemicals on the feed or upstream side.

Membrane Fouling - Plugging of a membrane surface or pores with contaminants, which can result in a decrease in the rate of flow of the desired chemical or water through the membrane.

Metabolite - A general term for a biological compound that is the product of an enzymatic reaction.

Molecule - A group of elements combined in a specific way; the smallest discrete entity of a specific chemical product.

Osmosis - The spontaneous movement or diffusion of a solvent, such as water, through a membrane to a more concentrated solution from a less concentrated solution.

Permeability - The ability of a membrane to allow passage of water or chemicals through the membrane.

Permselectivity or Permeation Selectivity - The extent that a membrane allows retention of some components while allowing another or others to pass through it; a measure of its separation capability.

Plasmid - Any one of a variety of small, circular DNA molecules that may be found free in the cytoplasm of a cell or bacterium, replicating more or less in unison with the chromosome of the cell, but in an autonomous way. They may be extracted in the form of a DNA preparation and artificially transferred to other cells ("transformation"). Depending on the genes they carry, they may endow the host cell with new properties.

Process Energy - The amount of energy required to process or convert a feedstock to a chemical product; can be expressed as Btu/lb.

Protein - The main chemical component of living matter. A protein molecule is a chain of up to several hundred amino acids and is folded into a more or less compact structure. Since some 20 different amino acids are used by living matter in making proteins, the variety of protein types is enormous.

Recombination - In genetics, a very widespread cellular mechamism by which segments of DNA may be exchanged between two different DNA molecules. When at least one of the molecules is circular, the result may be the insertion of one molecule into the other ("integration").

Reverse Osmosis (RO) - The most widely used membrane separation process, most often used to separate salt water to produce water for drinking or other uses (desalination). The feed mixture is pumped at high pressure to drive the more permeable component (water in desalination) through the membrane. It is called reverse osmosis because the pressure is applied to the feed stream in a direction opposite to the pressure of normal osmosis.

Rhodium - A metallic element that is sometimes present in certain, specific chemical catalysts.

Second Law Analysis - An analysis and determination of energy required to carry out a process which takes into account energy losses that result because of the second law of thermodynamics. This law limits the direction of flow of heat and the conversion efficiency of heat energy into other forms of energy, e.g., electrical or mechanical.

SECTION I

INTRODUCTION

A. PROJECT DESCRIPTION

1. The ECUT Program

The Energy Conversion and Utilization Technologies (ECUT) Program was established by the United States Department of Energy (DOE) in FY 1981 as a centralized, generic research and development subprogram within the Office of Energy Systems Research. The ECUT Program has two major goals:

(1) Evaluate new or innovative concepts for improved efficiency or alternate fuel use in energy conversion and utilization equipment.

(2) Expand the technology base necessary for development of improved energy conversion and utilization equipment.

2. The Chemical Processes Project

The Chemical Processes Project was one of six projects comprising the ECUT Program during FY 1982 (see Figure 1-1). This annual report describes the FY 1982 activities, accomplishments and future plans of the Project.

a. Background (Prior to FY 1982). The Chemical Processes Project was established in May 1980 to investigate and develop new techniques and reaction sequences for the chemical processing industry. Concurrently, JPL was selected as the Project's lead laboratory. DOE funding for the Project began in July 1981. Prior to this date, JPL assisted the ECUT Office in evaluating and prioritizing potential project work elements. These initial planning efforts resulted in the selection of two work elements for the Project--Catalysis (chemical catalysis and biocatalysis) and Separation.

During FY 1981, JPL started preparing biocatalysis and chemical catalysis advocacy papers and a multi-year plan for the Separation work element. Two research contracts were initiated at the California Institute of Technology (Caltech) in the Department of Chemistry and Chemical Engineering. The first focused on developing quantifiable relationships between biocatalysts produced by recombinant-DNA organisms and their environment. The second concentrated on developing efficient processes for hydrocarbon production in dilute (or waste stream) feedstocks.

b. FY 1982 Project Description. The FY 1982 Chemical Processes Project had the same two work elements (Catalysis and Separation) as in FY 1981. Catalysis research was broken down into two areas--Biocatalysis and Catalyst Modeling.

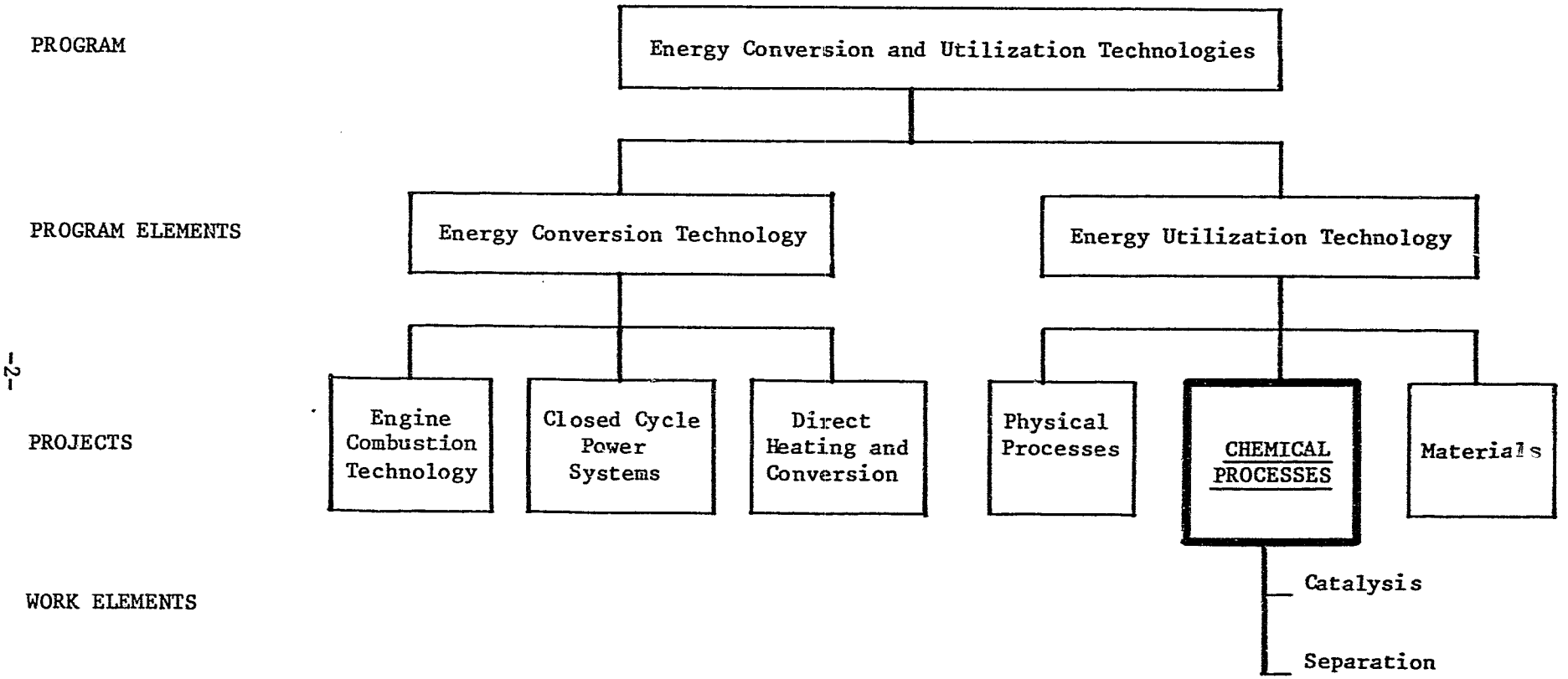

Figure 1-1. Relationship of the FY 1982 Chemical Processes Project to the Overall ECUT Program

Catalyst Modeling. Catalyst Modeling research concentrates on developing models for predicting and optimizing the reactivity of major heterogeneous catalysts. This research has three phases: (1) characterization of molecular interactions at the catalyst-reactant interfaces; (2) modeling and experimental validation of the mechanisms of catalytic reactivity; and (3) development and laboratory-scale verification of criteria and methods for selecting and optimizing catalysts.

Biocatalysis. Biocatalysis research focuses on resolving the major technical barriers that impede the potential use of biologically-facilitated continuous chemical production processes. These barriers include: maintenance of stable genotype in biocatalytically useful microorganisms; reduction of biological dependence on a water and dilute product environment; cellular-level operational requirements; process reactor-level operational requirements; and biocatalytic product separation technology optimization.

Separation. Separation research focuses on establishing the technical feasibility of innovative, low-energy intensive separation concepts. Activities involve investigating techniques such as membrane separation, supercritical fluid extraction and high-performance liquid chromatography.

3. Project Transition and Reorganization in FY 1983: The Biocatalysis Research Activity

In late 1982, the ECUT Program was reorganized. The Chemical Processes Project was consolidated and renamed the Biocatalysis Research Activity. Biocatalysis is now the primary research focus and work element. Catalyst modeling activities, now called Molecular Modeling, will continue but emphasize establishing the technical feasibility for theoretically-based design, optimization, and control of biocatalyzed and hybrid chemically/biologically catalyzed chemical production processes. The Separation work element was inactivated; however, separation technology activities relevant to biocatalyzed chemical production processes will be addressed under the Biocatalysis work element.

4. Goal and Objectives

The current goal of the Biocatalysis Research Activity is to sufficiently build the technical and engineering base of biocatalysis technology to enable industry to displace a significant level of non-renewable resource requirements by 2000. The activity has an objective for each work element:

- Biocatalysis. Establish the technical feasibility for continuous production of chemicals using biocatalyzed processes by 1990.

- Molecular Modeling. Establish the technical feasibility for theoretically-based design, optimization, and control of biocatalyzed and hybrid chemically/biologically catalyzed chemical production processes by 1997.

B. ORGANIZATION OF THE REMAINDER OF THIS REPORT

Sections II and III of this report present, respectively, the FY 1982 accomplishments of the Chemical Processes Project and the FY 1983 plans for the Biocatalysis Research Activity. Section IV lists a bibliography of reports and papers prepared or published by the Chemical Processes Project during FY 1982.

SECTION II

FY 1982 ACCOMPLISHMENTS OF THE CHEMICAL PROCESSES PROJECT

The Chemical Processes Project's activities during FY 1982 were organized into the Catalysis and Separation work elements and a supporting planning function (see Table 2-1). This section of the report describes the activities and FY 1982 accomplishments for each of these these areas.

Table 2-1. ORGANIZATION OF FY 1982 ACTIVITIES IN THE CHEMICAL PROCESSES PROJECT

WORK ELEMENTS		
CATALYSIS		SEPARATION
Biocatalysis	Catalyst Modeling	
• Kinetics for Process Design	• Microscopic Reaction Models for Catalytic Processes	• 2nd Law Analysis
• Techniques for Plasmid Monitoring	• Electrocatalysis	• Membrane Technology
• Cellulase hyper-production	• Decarboxylation	• Critical Fluid Extraction
• Membrane Fouling	• Ammonia Synthesis	

PLANNING SUPPORT
• Guidance and Evaluation Panel
• Energy and Economic Analysis
• Multi-Year Research Agenda
• Plan for Separation Technology Program

A. CATALYST MODELING

Catalyst Modeling research activities encompassed four research activities (Table 2-1): (1) Microscopic Reaction Models for Catalytic Processes; (2) Electrocatalysis; (3) Decarboxylation; and (4) Ammonia Synthesis.

1. Microscopic Reaction Models for Catalytic Processes - California Institute of Technology, Department of Chemistry and Chemical Engineering

a. Description. This research involves modeling the Fischer-Tropsch (F-T) class of reactions in which synthesis gas (CO/H_2) is converted directly to alkanes, alkenes, and alcohols (or other oxygenates). The principal problem in these systems is the lack of selectivity: most commercial Fischer-Tropsch catalysts involve very complicated recipes, the basis of which are completely empirical. The goal of this modeling effort is to establish the critical features that need to be incorporated into effective catalysts and to provide a model that will allow one to adjust these features so as to optimize performance under actual operation conditions.

b. FY 1982 Accomplishments

- The parameters for the force fields required for the calculation of the dynamics of the (F-T) class of reactions has been developed. Preliminary conclusions are:
  - stabilization of metal formyls for Group VIII metals are not important in F-T processes;
  - species analogous to the metal alkylidine complexes involved in metathesis catalytic RXNS are quite unlikely for a role in F-T chemistry; and
  - examination of the energetics of F-T processes on Ni clusters suggest that there may be a lower energy for propagation than for methane production (this is consistent with the large amount of higher hydrocarbons formed over Ni at low temperatures).

2. Electrocatalysis - Rockwell International Microelectronics Research and Development Center

a. Description. The goals of this research are: to evaluate the major technological areas in which advances in electrocatalysis could have a large impact on the national energy picture; and to perform preliminary experimental research on electrocatalytic systems which offer a large energy payoff.

Current key problems of general importance in electrocatalysis include the oxygen electrode whose irreversibility at practical electrodes leads to large energy inefficiencies, and the lack of good catalysts for reducing C_1 compounds and for fixing nitrogen.

b. FY 1982 Accomplishments

- The major technological areas in which electrocatalysis has a potential for significant energy savings were identified. They are as follows:

  - Inorganic electrosynthesis - This area includes chlorine synthesis and aluminum production which together consume about 5% of the total U.S. energy production. Another important process which is expected to play an increasingly important role is electrolytic hydrogen production.

  - Organic electrosynthesis - In principle, electrosynthesis is a more energy efficient way of producing organic compounds since, compared to thermal conversion processes, reactions are performed at lower temperature and are more reversible. Currently, adiponitrile is produced by electrosynthesis on a large scale (200,000 metric tons/yr).

  - Electrochemical energy production - Photoelectrochemical cells are in the early stages of development, but represent an attractive long-term means of solar energy conversion.

  - Electrochemical energy storage - Electrocatalysis plays an important role in the performance of most battery and fuel cell systems, particularly those involving gas producing/consuming electrodes (e.g., air or oxygen cathodes and hydrogen anodes). The energy impact of these systems is difficult to assess but will undoubtedly be significant.

- Perovskite-type, lanthanum nickelate compound was synthesized. This compound shows promise as an effective oxygen electrocatalyst.

3. Decarboxylation - Jet Propulsion Laboratory

a. Description. Dilute streams of organic acids are byproducts of fermentation processes, paper and pulp industry waste streams and processed urban waste. Currently, these are dumped since no method exists to extract the acids unless the streams are first concentrated. A catalytic process which would convert these dilute acids to useful chemicals such as alcohols and hydrocarbons would allow their utilization as a high volume alternate, non-fossil feestock of approximately 10^6 tons/year for the chemical industry providing up to 10^{13} Btu annually. Also, energy conservation at the quad level could result from substituting petroleum-based feedstocks in new, more energy efficient hybrid chemical catalytic/biocatalytic processes.

The desired conversion pathway involves loss or expulsion of carbon dioxide from each molecule of the acid (i.e., their decarboxylation) to generate alcohols and hydrocarbons which are widely used as intermediates in the chemical industry. Currently, there are no catalysts available for this process which can efficiently convert dilute acid streams, although Ce^{4+} promoted with I_2 slowly decarboxylates concentrated acids.

Previous investigations have indicated that transition-metal catalysts and catalyst-modified electrodes can be developed that would be effective on dilute acid streams. Therefore, work was initiated at JPL to develop new catalysts for decarboxylation of acids in aqueous solutions.

b. FY 1982 Accomplishments

- A rhodium-based catalyst was prepared and preliminary experiments were completed where the catalyst appeared to decarboxylate dilute acids at concentrations of 1-10 Vol %. However, the results were not consistently reproducible at 1% concentration and no kinetic measurements have been made. Further work is required to define the catalyst systems, mechanism, and practical limitations and to determine decarboxylation rates, yields, and susceptibility to poisoning or inhibition.

- The novel use of diagnostic techniques such as ESR spectroscopy and electrochemistry leading to some initial characterization of reactive intermediates in these systems has been examined. This type of characterization will lead to reactivity models which may be used to optimize the chemical structure of certain rhodium catalysts for the best turnover rate/stability trade-off.

- Evaluations of novel hybrid chemical/biological processes for the production of hydrocarbon chemicals have been initiated. An example of a hybrid process proposed (Levy, et al, 1981) is conventional electrolysis (i.e., Kolbe synthesis) dilute acids from a fermentation reactor. However, state-of-the-art technology would require about 5000 Btu/lb or nearly 25% of the energy of the product for the conversion of the acids to hydrocarbons. New catalyst systems could decrease the decarboxylation energy requirement to 2000 Btu/lb of product by eliminating the most energy-intensive process steps, which are separation of the acids and Kolbe electrolysis. The significance of this decrease in energy consumption is that the ratio of product energy/process energy for the overall hybrid process could increase to approximately ten, compared with the value for conventional production of hydrocarbon fuel which has been estimated at six (Hopkinson, et al, 1980). Thus, it should be practical to produce low molecular weight hydrocarbons from renewable resources with significantly less process energy consumption than for production from non-renewable petroleum.

4. Ammonia Synthesis - Jet Propulsion Laboratory

a. Description. This study involves examining the industrial ammonia production process to determine the potential energy savings which could result from improving the conversion efficiency of the ammonia synthesis catalyst. A base case has been taken from the energy consumption and production statistics of a large ammonia plant. Three other scenarios have been examined that used varying degrees of catalyst improvement reflected in temperatures of operation. The plant has been treated as if the catalyst was retrofitted into the reactor while feedstreams were held constant.

b. FY 1982 Accomplishments

- This study was completed. It was determined that retrofit installation of catalysts which would operate at lower temperature and approach equilibrium conversion could result in significant energy savings. Also, results indicated that improved catalyst systems and new technology could lead to a total of up to 30% increase in thermal efficiency of synthesis gas/ammonia production from natural gas.

B. BIOCATALYSIS

As shown in Table 2-1, the Biocatalysis work element comprised four research activities: (1) Kinetics for Process Design; (2) Techniques for Plasmid Monitoring; (3) Cellulase Hyperproduction; and (4) Membrane Fouling.

1. Kinetics for Process Design - California Institute of Technology, Division of Chemistry and Chemical Engineering

a. Description. The population statistics on the number and expression rate of E. coli plasmids are necessary for assessing the production of plasmid-encoded gene products for a chemical process. The controlling sequence for genes carried by many popular expressing vectors are the lac promoter-operator.

The rate at which a gene is read and copied into the form of messenger RNA by the enzyme RNA polymerase is a major determinant of the rate of synthesis of the gene product (usually an enzyme) within the cell. A small regulatory region of DNA adjacent to the structural gene, the promoter, is the attachment site for RNA polymerase. Promoters such as that for the gene ß-galactosidase in E. coli (lac promoter) are routinely attached to cloned genes in order that they may be turned on and off in a recombinant organism by the investigator. A quantitative understanding of lac promoter behavior in multicopy plasmids will permit rational design and optimization of organisms and reactors for recombinant biocatalyst production.

The amount of enzymes accumulated within the cell is also dependent on the number of gene copies contained in the cell, which in turn depends upon the

number of plasmid molecules per cell. Cellular plasmid content is regulated by a particular DNA sequence in the plasmid called the origin of replication. λdv is a plasmid derived from the E. coli bacteriophage λ which replicates autonomously in E. coli. Its replication (and the cloned genes which it may contain) is regulated by several repressor and initiator proteins which are relatively well characterized. This system provides the best starting point for quantitative understanding of plasmid replication control.

b. FY 1982 Accomplishments

- A detailed mathematical model which describes the regulation of the lac promoter at the molecular level has been formulated and shown to be consistent with experimental data spanning a wide range of genetic backgrounds and cell environments. The model has been applied to calculate the regulation of gene expression in recombinant microorganisms in which the lac promoter is used to regulate expression of a plasmid gene. For example, the model was used to investigate the effect of the number of plasmid molecules in the cell on the amount of product synthesized, with the interesting result that an optimum value is predicted, beyond which larger numbers of plasmids give reduced levels of product. This is just one illustration of the possible applications of a very powerful and generally applicable mathematical description of regulatory processes in recombinant cells which can be used to design and optimize process reactors.

- The regulation of λdv plasmid replication by a series of repressor and initiator proteins has been described by a mathematical model which should be useful in describing the population behavior of λdv recombinant cells. This model of λdv plasmid replication has been refined and tested against experimental data. The model's kinetic equations include the molecular interactions known to exist and known to be important in regulating replication of the plasmid. By combining this model with available data in the literature on growth rate effects on several different kinds of cell reaction processes, the growth rate has been related with levels of gene expression for recombinant systems containing the λdv plasmid.

2. Techniques for Plasmid Monitoring - California Institute of Technology, Department of Chemistry and Chemical Engineering

a. Description. Synthesis of protein products encoded by plasmid genes in recombinant cells depends upon a variety of host cell constituents. Conversely, the presence of the plasmid and its protein products may have deleterious effects upon growth and macromolecular synthesis in the host cell. To understand the stability of plasmids in recombinant cells it is

necessary to develop a technique whereby a growing population can be sampled and large numbers of individual cells can be assessed for their plasmid contents. This measurement technique must prevent interference between cells containing a plasmid marker (a particular enzyme) and cells lacking the enzyme. Such interference arises by diffusion of the fluorescence marker used for the experiment from one type of cell to the other.

b. FY 1982 Accomplishments

- A technique was developed whereby the plasmid-encoded enzyme, ß-galactosidase, acted upon a fluorogenic substrate, Naphthol-AS-BI-ß-D-galactopyranoside, which was measurable by flow microfluorometry. The level of fluorescent product in a cell reflects the number of its copies of the ß-galactosidase gene.

- The problem of flourescence marker diffusion between different cell types has been solved and experimentally-verified by the use of an additional reaction which traps the fluorescent product on the enzyme-catalyzed reaction within the cell containing the enzyme.

3. Cellulase Hyperproduction - Jet Propulsion Laboratory

a. Description. The fourth quarter of FY 1982 was the initial period of work on the optimization of fungal cellulase production. The two main purposes of this effort are: first, to be able to genetically alter the metabolic regulation of cellulolytic fungi so that they continually synthesize cellulases at high rates; and, second, to augment the secretion of the enzymes as a strategy for reducing purification steps and costs.

b. FY 1982 Accomplishments

- Conditions for the growth of the reference organisms, Trichoderma ressei, were established for semisolid and liquid media using complex nutrients and minimal media employing lactose and cellulose as carbon sources.

- Modification of the above media with antibiotics and nonionic detergents enabled the development of a plate clearing assay on cellulose agar for the identification of fungal colonies which secrete cellulase. This assay will be used in the identification of hyperproducing and nonproducing mutants. Parameters to balance were growth rate of the mycelia, diffusion rates of enzymes and efficiency of enzyme release from growing fungi.

- A filter paper degradation assay was established for measuring complete celulase activity in culture filtrates and electrophoretic patterns of filtrates correlated with

enzymatic activity to identify cellulase polypeptides. Variation of culture medium composition demonstrated control of enzyme synthesis by carbon source.

- A use permit for plant pathogenic strains of Fusarium fungi was obtained from the U.S. Department of Agriculture and 18 strains were acquired from the American Type Culture Collection.

- Preliminary characterization of Fusarium strains has begun with respect to culture conditions and enzyme production on both solid and liquid media.

- Preliminary characterization of the genetic complexity of the Fusarium strains has begun by examination of total cell DNA and RNA by agarose gel electrophoresis.

4. Membrane Fouling - Jet Propulsion Laboratory

a. Description. Energy requirements for separating and purifying products such as ethanol or butanol from biocatalyzed fermentation processes consume the largest portion of process energy. Since membrane systems require substantially less energy for separation than most alternatives (for example, distillation), they have been suggested for separation or concentration of fermentation products. However, earlier experiments on membrane applications in relatively complex aqueous mixtures, such as fermenter supernatent, food products, and sludge water, have shown that concentration polarization and membrane fouling cause problems that seriously affect the general applicability of membrane systems for separation.

This research activity involved reviewing previous work in this area to provide a preliminary assessment of the potential of membranes for separation of fermentation products.

b. FY 1982 Accomplishments

- This research activity was completed during FY 1982. A technical summary of the results follows.

  The various types of membrane processes include microfiltration (MF), ultrafiltration (UF), reverse osmosis (RO), dialysis, electrodialysis (ED), and gas separation. Except for dialysis and electrodialysis, these processes are driven by pressure differences across the membrane. MF, UF, and RO are similar processes, with RO requiring the highest pressure gradient (20 to 100 bar). It is also the most selective and, therefore, is of greatest interest for separation of fermentation products. However, RO is also the most adversely affected by concentration polarization.

Concentration polarization is the presence of a higher concentration, Cs, of rejected (nonpermeating) species at the membrane surface than in the bulk solution. Even in the absence of any fouling (decreased transmembrane flux caused by particles or precipitation of dissolved materials at the upstream surface, or within the membrane), concentration polarization causes decreased permeation because of increased osmotic pressure at higher concentration relative to the concentration downstream of the membrane. The two main consequences of concentration polarization are that increased pressure is required to maintain a reasonable flux as the concentration of rejected species increases (until a limit of 20 to 40% concentration is reached), and that foulants are concentrated and precipitate when their solubility limits are exceeded. Furthermore, fermentation broth contains products that are known to contribute to severe fouling, such as organic fragments, proteins, and colloids.

Highlights and conclusions of this review are as follows:

- Membrane processes are applicable to streams requiring concentration to less than 40%.

- For applications to biocatalytic processes, the adverse effects of concentration polarization and fouling are relatively severe.

- An efficient process may be developed based on initial concentration by RO, followed by an efficient distillation process. However, if the product is more volatile than water, such a process would not be very energy efficient or effective because of the need to separate large amounts of water from small amounts of product.

- Evaporative processes for desalination of water are still highly competitive with RO because of higher costs of pretreatment, membrane replacement, and fouling, even though desalination is more ideally suited to RO than most other processes for purification.

- Membrane systems for separation of fermentation products are not necessarily more energy efficient or cost effective than alternative separation processes.

- Pervaporation, which is selective permeation of the desired product in the vapor phase through a membrane, may be appropriate for purification of specific fermentation products; however, some net product distillation energy would be consumed.

- It will be necessary to make detailed energy-economic assessments of proposed separation alternatives followed by experimental validation and to establish the most energy efficient, economically viable separation technology to be used for any specific fermentation process.

C. SEPARATION

The first phase of the Chemical Processes Project consisted of efforts to define process steps in chemical processes that consumed large amounts of energy, where increases in efficiency could lead to substantial decreases in total energy consumption. It was determined that for production of chemicals, improvements in product separation could result in the largest increases in energy efficiencies. Therefore, three research activities in advanced separation technology were undertaken to attempt to define specific areas for potential advancements in energy conservation: 2nd Law Analysis; Membrane Technology; and Critical Fluid Extraction (Table 2-1). (A plan for a separation technology program was also prepared and is discussed in subsection D of Section II.)

1. 2nd Law Analysis - Engineering Research West (ERW)

a. Description. The objectives of this activity are: to develop an analytical method based on the second law of thermodynamics to provide a general and uniform basis for comparing the energetics of separation processes; to identify the energy-intensive steps of separation processes; and, to determine if meaningful and practical energy reductions can be realized for candidate and/or proposed separation techniques and application areas.

b. FY 1982 Accomplishments

- The initial phase of this research was completed. The major findings were as follows:
  - Identification of the Energy-Intensive Steps in Each of the Three Analyzed Processes - Membrane processes consume work by forcing material through membranes and equipment with small tolerances and by depletion of the permeating species at the upstream surface of the membranes. Supercritical extraction processes consume work primarily from losses associated with inefficient pressure recovery. Chromatographic methods use energy largely in proportion to the amount of solvent needed to effect separation.
  - Energy Loss as Low-Grade Heat - The industry-average temperature for discharging low-grade heat to cooling towers is about 78°C. This represents about 15% of the chemical process energy.

- Separation of Oxygen from Air - The work of separation at 25°C is 335 kcal/kg-mol of air (approximately 0.0134 kWh/kg of air). At $0.065/kWh electrical cost, this amounts to about $21.12 per ton of air. The actual consumption by commercial liquefaction is about 4 times the theoretical value. Analysis of a 5-stage membrane process indicates that energy consumption would be reduced to 57% of that used in commercial liquefaction processes.

- Efficiency of a Pressure Cycle - The concentration of extracted products in supercritical fluids is a function of pressure, increasing and decreasing directly with corresponding changes in pressure. Extraction is carried out at high pressure, and product release is carried out at low pressure. About 30% of the mechanical work in a real pressure cycle is lost. This loss of mechanical work is the primary energy inefficiency in supercritical extraction.

2. Membrane Technology - Bend Research, Inc.

a. Description. This research activity's objective was: to carry out a study assessing the current status of membrane technology; to identify industrial processes in which membrane technology could effect energy savings or other advantages; and, to identify advanced and new concepts of membrane technology that require research support and would offer the potential of achieving beneficial gains in energy efficiency.

b. FY 1982 Accomplishments

- Application areas for potential energy efficiency using membrane technology were identified. They include:

  - The separation of the acid gases, and particularly CO_2, from natural gas streams to upgrade the gas stream and to recover the CO_2 for use in secondary oil recovery.

  - The recovery of oxygen and nitrogen from air with facilitated-transport membranes. Oxygen-enriched air can be used in synfuels production, and nitrogen can be used for "blanketing" and other industrial applications.

  - The separation of ethanol or other potential substitute liquid fuels from the liquors produced in fermentation tanks using biomass sources.

- The recovery of heat from industrial drying processes. Most of that heat is present in the water vapor and could be recovered by passing the vapor through an air-impermeable membrane.

- The recovery of metals from the hydrometallurgical leach solutions now prevalent in the mining industry by coupled-transport membranes.

- The concentration and separation of acids, bases, and salts in solution by a form of ion exchange known as Donnan dialysis.

- The generation of acids and bases by means of so-called bipolar membranes.

- Chemical or biochemical conversions in which immobilized catalysts are combined with membrane separators.

- The direct production of energy from sunlight by means of membranes containing chlorophyll analogs.

- Research and development activities for membranes were identified. As membranes are especially suited to achieve partial separations, the possibility of reducing energy requirements and overall costs by combining a first-stage membrane process with a second-stage cryogenic, distillation, absorption, or other type of process may be a high potential application. Recommended research areas include:

  - enhancement of membrane permeability and permselectivity; liquid membranes; and,

  - high-performance coupled- and facilitated-transport mechanisms.

3. Critical Fluid Extraction - Critical Fluid Systems

a. Description. The objectives of this research were: to carry out an assessment of the potential for critical-fluid extractions as a separation process for improving productive use of energy in the process industries; and to provide recommendations for long-term research and development.

b. FY 1982 Accomplishments

- Application areas for energy-efficiency with supercritical extraction were identified and include:

- separation of both synthetic and biosynthetic chemical mixtures from aqueous solutions. Table 2-2 is a tabulation of distillation energy consumption for a variety of commercial, oxygenated organic compounds when separated from water solution. Note the high consumption of 9008 Btu/lb for ethanol. Analysis of a supercritical extraction of ethanol from water indicates an energy consumption of 1000 to 1500 Btu/lb.

- natural products, including foods such as vegetable oils.

- fossil fuels, such as petroleum, coal, and possible tarsands, heavy crudes, and shale.

• Research areas for Supercritical Extraction were identified and include:

- co-solvents to increase extraction concentrations to decrease energy per pound of product for each pressure cycle.

- chemical reactions in supercritical solvents - There are no published data available on the effects of carrying out chemical reactions near the critical point, relative to liquid or gas phases, in either catalyzed or uncatalyzed systems. At this stage, such studies must of necessity be purely exploratory. Fundamental questions that require answers concern the possibilities of kinetic and chemical mechanism changes that may occur in this regime, with fluids acting as low-density liquid solvents. While the uncertainty in this area is great, the potential payoff for many chemical syntheses could be very significant. The consequences of improvements in chemical-reaction systems would include production of more concentrated products and reduced reactor volumes, both of which have substantial implications for energy productivity. Studies of both homogeneous and heterogeneous catalysis in this regime would be of great interest.

D. PLANNING SUPPORT

Planning support activities for the Project included the Guidance and Evaluation Panel, the Energy and Economic Analysis, Multi-Year Research Agenda, and the plan for a Separation Technology Program (Table 2-1).

1. Guidance and Review Panel

a. Description. The Project has formed a biocatalysis advisory group consisting of representatives from the chemical processing industry,

Table 2-2. Water-Oxygenated Organics Distillation Energy Consumption

COMPONENT	TOTAL U.S. DISTILLATION ENERGY CONSUMPTION (quads/yr)	SPECIFIC DISTILLATION ENERGY CONSUMPTION (Btu/lb product)
Ethylene Glycols	0.01065	2,795
Ethanol	0.01063	9,008
Phenol	0.00947	4,344
Adipic Acid	0.00739	4,862
Methanol	0.00733	1,175
Vinyl Acetate (monomer)	0.00710	4,797
Acetic Acid	0.00701	2,885
Isopropanol	0.00651	3,785
Ethylene Oxide	0.00554	1,325
Methyl Ethyl Ketone	0.00481	9,431
Terephthalic Acid	0.00425	1,756
Acetone	0.00417	2,172
Dimethyl Terephthalate	0.00412	1,567
Formaldehyde	0.00412	733
Acetic Anhydride	0.00267	1,669
Propylene Oxide	0.00219	1,217
Glycerine	0.00202	14,870
Acetaldehyde	0.00174	1,081
AVERAGE		2,366
TOTAL	0.10172	

genetic engineering firms and universities. The Panel's charter encompasses advising the Project on the desirability of specific research activities and guiding research activities in progress.

b. FY 1982 Accomplishments

- The Guidance and Review Panel was established. Panel members include:
  - J. Bailey, California Institute of Technology
  - E. Dunlop, Washington University
  - J. Eberhardt, U.S. Department of Energy
  - R. Gomez, Genentech, Inc.
  - L. Kim, Shell Oil, Inc.
  - J. Moacanin, Jet Propulsion Laboratory
  - W. Weigand, National Science Foundation

- Three initial priority areas for biocatalysis research were defined in terms of requirements for potential applicatons:
  - Reduced product/solvent concentration;
  - Increased rates of reaction; and
  - Increased size or altered structure of genetic information.

2. Energy and Economic Analysis - Chem Systems, Inc.

a. Description. This research activity has focused on developing and demonstrating an economic assessment methodology for comparing conventional and biocatalyzed chemical production processes. Initial modeling efforts have used a state-of-the-art fermentation process for acetone/butanol/ethanol (ABE). The objective has been to establish a candidate base case for comparison with new processes that will be developed as a result of research advances in biocatalysis. The defined ABE production facility consists of three major sections: (i) pretreatment and enzymatic hydrolysis of wood, (ii) fermentation, and (iii) purification.

b. FY 1982 Accomplishments

- The initial base case model - a preliminary technical and economic evaluation of the ABE production process via fermentation - was completed. The study considered two separate cases in an attempt to provide some quantitative insight into the sensitivity of overall plant economics to certain fermentation design parameters. The fermentation of wood-derived sugars by Clostridium acetobutylicum has a maximum yield at 3 percent initial sugar. This yield begins to decrease as initial sugar concentration is increased beyond 3 percent. At 6 percent initial sugar, microorganism activity falls to zero due to the level of butanol toxicity associated with this sugar concentration (approximately 1.3 percent butanol). Therefore, product yield is maximized at 3 percent initial sugar while product concentration is maximized at 6 percent initial sugar. The two cases considered were taken at two available data points, one representing the maximum yield case at 3 percent initial sugar, and the other increasing the initial sugar concentration to 5 percent while sacrificing yield. In this way, the maximum yield case minimized raw material consumption, while the lower yield case reduced capital and energy requirements in the purification section.

  The analysis showed that the mixed solvent (which consists mostly of n- butanol) could be produced for 2.83 dollars per gallon for the maximum yield case as compared to 2.58 dollars for the lower yield case. In both cases approxi-

mately 40% of the cost was required for purification. Furthermore, the purification section consumed all the net energy required, but for the lower yield case the total non-renewable energy required was about 60% of that needed for conventional synthesis from propylene feedstock. However, the cost of production (lower yield case by fermentation) was 10% more than by conventional synthesis. Elsewhere it has been projected that the cost of production by a fermentation process will be equal to the cost for conventional synthesis by the mid-1980s because of the expected increases in energy costs.

From this analysis, it is clear that future research and development in ABE fermentation should be directed toward reducing energy consumption and costs associated with solvent purification. Two approaches were suggested:

- Development of improved separation techniques such as membrane separation, supercritical fluid extraction, or absorption, which have great potential for reducing energy consumption during ABE purification.

- Development of an improved microorganism via genetic manipulation which can satisfactorily ferment wood sugars and can tolerate high concentrations (greater than 1.3 percent) of butanol in the fermentation reactor.

3. Multi-Year Research Agenda - Jet Propulsion Laboratory

a. Description. A major planning effort was undertaken in FY 1982 to develop a multi-year agenda for the Chemical Processes Project. This activity focused on describing the rationale, strategy, objectives, future activities, and resource requirements for biocatalysis, and catalyst modeling research.

b. FY 1982 Accomplishments

- This activity was completed and a final report entitled the Multi-Year Research Agenda was published. The Research Agenda presents an overview of the chemical processing industry's problems of high-cost energy, under-utilization of capacity, and increasing foreign competition. The required research and development paths for addressing these problems (i.e., improving yields from conventional feedstocks, conserving conventional fuel-based process energy, and utilizing alternative/renewable feedstocks and fuels) are outlined. The agenda defines the role of the Energy Conversion and Utilization Technologies Program in general, and the Chemical Processes Project in detail, in supporting the advanced aspects of this research.

For biocatalysis research, the Agenda outlines a fifteen-year program to establish the technical feasibility of using genetically-engineered microorganisms to produce chemicals in bulk quantities. Research activities during this period would focus on defining and verifying the scale-up parameters for biocatalyzed chemical production processes.

For catalyst modeling research, the Agenda describes a ten-year program for establishing the technical feasibility for theoretically-based design, optimization, and control of inorganic chemical process catalysts. Research activities would focus on molecular-level modeling of the reaction mechanisms of heterogeneous catalysts.

4. Plan for Separation Technology Program - Jet Propulsion Laboratory

a. Description. This activity was initiated to review and intergrate information in the vast and diverse field of separation technology. The planning effort focused on achieving a comprehensive perspective to identify future areas of industrial significance for which energy-efficient separation techniques or methods should be developed.

Separation methods can be typically classified under two headings, "conventional" and "emerging." Examples of conventional methods are distillation, filtration and evaporation, which are in widespread industrial use and familiar to virtually every chemical engineer. Emerging methods include all others which may be in various development stages ranging from concept, laboratory, and pilot plant to very limited, low-level industrial use. Examples of energy efficient emerging methods include freeze crystallization, liquid membranes, supercritical extractions, and others listed in Table 2-3.

b. FY 1982 Accomplishments

- An internal planning document was completed and published. The findings and recommendations included the following:
  - No single organization or individual was found to have a comprehensive perspective of future trends in separation technology; however, a number of organizations and individuals involved in R&D have well-developed perspectives of discrete segments in the field.
  - Since federal support for separation R&D will be low-level compared to industrial funding, government investments should open new ground rather than advance an already advanced technology.

Table 2-3. Separation Methods for Chemical Process Applications

CONVENTIONAL	EMERGING
Distillation	Supercritical Extraction
Evaporation	Liquid Membranes
Absorption	Electrochemical Membranes
Extraction	Freeze Crystallization
Filtration	Electrodialysis
Solid Membrane	Magnetic Fractionation
Reverse Osmosis	Absorption
Centrifugation	Chromatography
	Ultrafiltration
	Solubility-Adjusted Precipitation

- Specific-idea concepts identified:

  1) Coupled Processes

     a) Modify the value of reject species in a mixture to achieve a more efficient separation when using an energy efficient separation method. Using liquid or solid membranes as an example, the reject species could be complexed with another agent to significantly increase the physical size of the combination, and thus reduce its tendency to permeate relative to the value species. Another novel approach might be to complex the value of reject species with a magnetic compound and then achieve separation by magnetic fractionation.

     b) Combine freeze concentration and multiple-effect evaporation (with vapor compression feature) to achieve an energy efficient system. But in general, seek to identify potential application areas for coupled-processes.

     c) Increase the fermentation yields of alcohol-water solutions to reduce separation work and therefore achieve energy reduction in the separation step.

  2) New Concepts

     a) Investigate chemical reactions requiring a catalyst in supercritical fluids functioning as reaction solvents. Desirable chemical reactions selected for study could be those

involved in "bottom up" chemistry, which produce industrially important chemicals. Products would be separated out using the energy efficient pressure/solubility properties of supercritical fluids. Unknowns in supercritical solvents are chemical kinetics, product distribution, product yield, and catalyst behavior. Critical Fluid Systems, Inc. has demonstrated that supercritical solvents can be used to clean and reactivate absorbent-grade charcoal. Perhaps supercritical solvents can clean catalysts and extend catalyst lifetime, which itself would be an energy-saving step.

b) Development of a moving-bed-chromatography apparatus. This concept involves counter current movement of the absorbent media relative to the incoming feed stream. A trial calculation suggests enormous separation power for ethylene/ethane gas mixtures compared to separation in a stationary chromatographic column. Currently, ethylene/ethane mixtures are separated by an energy consuming cryogenic distillation.

c) Development of magnetic complexing compounds for important or emerging industrial chemicals.

SECTION III

FY 1983 PLAN FOR THE BIOCATALYSIS RESEARCH ACTIVITY

As discussed in Section I, research activities continuing from the FY 1982 Chemical Processes Project will be consolidated under the Biocatalysis Research Activity. The organization of these "continuing" activities is shown in Table 3-1 along with planned and proposed new research thrusts.

Table 3-1. Organization of FY 1983 Activities in the Biocatalysis Research Activity

WORK ELEMENTS	
BIOCATLAYSIS	MOLECULAR MODELING
• Kinetics for Process Design • Techniques for Plasmid Monitoring • 2nd Law Analysis of Separation Technologies • Cellulase Hyperproduction • Chromosomal Amplification • 1-2 Other New Research Activities	• Electrocatalysis • Catalyst Modeling

PLANNING SUPPORT
• Guidance and Evaluation Panel
• Energy and Economic Analysis
• Review of International Programs
• Research Opportunity Notice

This section will briefly describe the FY 1983 content of each of the three Biocatalysis Research Activity work elements: Biocatalysis, Molecular Modeling and Planning Support.

A. BIOCATALYSIS

1. Continuing Research

Four of the research activities started previously will continue in

FY 1983: Cellulase Hyperproduction; Kinetics for Process Design; Techniques for Plasmid Monitoring; and 2nd Law Analysis.

2. New Research

New research activities during FY 1983 will include work on Chromosomal Amplification and one or two other research areas yet to be announced.

a. Chromosomal Amplification. The application of genetic engineering techniques in certain bacteria may lead to greatly reduced production costs for some organic chemicals. However, before this potential can be realized in large-scale industrial processes, a method must be developed for stabilizing and retaining genetically-engineered traits (i.e., capabilities) in large quantities ("cultures") of bacteria.

A number of steps are required to genetically-engineer a bacterium to yield a valuable product. First, the gene (instruction sequence) responsible for directing the bacterium to produce the protein of interest must be isolated and joined ("spliced") to the DNA of an appropriate plasmid. This plasmid is then introduced into a bacterium ("transformation") where the plasmid will multiply ("amplification"), and a strain of bacteria will be established that carries multiple plasmid copies in each bacterial cell. The existence of the foreign gene in numerous plasmid copies results in higher yields of the desired product than if only a single or a few plasmid copies had the desired recombinant trait. Since bacteria can be grown on relatively inexpensive feedstocks (e.g., biomass), production costs for some organic chemicals may be significantly lower if genetically engineered processes can be cheaply scaled up.

One of the major technical barriers constraining such a production process arises from the typical characteristic of plasmids to float freely in bacterial cytoplasm, unconnected to the chromosome. Since only chromosomes, and not plasmids, consistently duplicate themselves before a bacterium physically divides and grows into two parts, the number of plasmid copies in each bacterium after division is not stable (i.e., the number may either increase or decrease). If the plasmid multiplies too much, it can overburden and kill the carrier bacterium; if it multiplies too little, as the bacterium multiplies, the plasmid is lost. In fact, plasmid loss in scaled-up bacterial cultures appears to be a significant shortcoming of the general technique of plasmid splicing.

This research activity is testing the possibility of solving the plasmid stability problem by inserting the genetically engineered plasmid directly into the bacterial chromosome, and amplifying it (or just the foreign gene) in place. Since the plasmid with its foreign gene of interest would then be part of the bacterial chromosome, the desired recombinant trait could not be easily lost as the bacterium multiplies.

This new technique will require several stages. First, the plasmid must be given the capability to insert itself into the bacterial chromosome. The DNA of certain bacteriophages already possess this capability through a special form of recombination. Plasmids can acquire this property if genes from these

bacteriophages are genetically-engineered into the plasmid. Once the plasmid is inserted into the bacterial chromosome, a first level of amplification (i.e., a doubling of the introduced gene) may occur through spontaneous duplication. This rare event, still incompletely understood, is required for the bacterium to have higher yields of the desired product. (This requirement coincides with the need for multiple plasmid copies in conventional plasmid splicing systems in order to have higher yields.) After the first gene duplication "repeat," the ordinary mechanisms of the cell may cause additional repeats to be formed, or alternatively, the first repeat may be lost. It will be necessary to isolate those bacteria where multiple repeats have been formed, and by genetic means inactivate this mechanism so the chromosome's "amplified" state will be stablized.

The stability of bacterial strains resulting from these manipulations will be compared with the stability of strains created by conventional plasmid splicing techniques. While this research is using laboratory strains of E. coli, the general principles involved could easily be applied to other types of bacteria.

B. MOLECULAR MODELING

1. Continuing Research

The Electrocatalysis and Catalyst Modeling activities will continue in FY 1983; however, both efforts will stress research areas relevant to biocatalysis.

The Electrocatalysis activity will focus on developing transition metal complexes as electrocatalysts for nitrogen fixation. The initial phase involves examining the electrocatalysis of dinitrogen (N_2) reduction by organometallic models of nitrogen-assimilating enzymes. Rockwell plans to develop chelating diphosphine complexes of molybdenum: These complexes appear to be considerably more robust than isolated enzymes and are promising candidates for a nitrogen-fixing cycle.

The Catalyst Modeling effort will focus on examining biocatalytic and hybrid biologically/chemically catalyzed processes. This will consist of developing force fields and stochastic treatment of the dynamics for reactions described by the force fields. Initially, thermolysin (a thermostable, CA-binding enzyme) will be examined.

2. New Research

No new research contracts in Molecular Modeling are planned in FY 1983.

C. PLANNING SUPPORT

1. Continuing Research

The Guidance and Evaluation Panel will review and select research

topics to be included in the Research Opportunity Notice (discussed below) and subsequent competitive solicitations. Also, the Panel will further develop the definitions of technical and economic issues relevant to biocatalyzed chemical production processes in the context of industrial interest and ECUT objectives.

The second phase of the Energy and Economic Analysis will begin. This effort will include an assessment of energy and economic impacts of expected generic research advances on fermentation process design and engineering.

2. New Research

A Research Opportunity Notice (RON) will be issued by the Jet Propulsion Laboratory during FY 1983 to notify industry and universities of and solicit their interest in conducting research for the Biocatalysis Research Activity. The RON will be a prelude to a Request for Proposal (RFP) cycle, and will help identify biocatalysis technical issues of greatest generic research interest.

SECTION IV

BIBLIOGRAPHY

A. FY 1982 REPORTS

The following is a list of reports prepared for the Chemical Processes Project during FY 1982.

Bailey, J. E., Lee, S. B., Srienc, F., and Hjortso, M., Kinetics of Product Formation and Plasmid Segregation in Recombinant Microbial Populations, California Institute of Technology, Annals of the New York Academy of Sciences, Biochemical Engineering III, 1983.

Chem Systems, Inc., Technical and Economic Assessment of Processes for the Production of Butanol and Acetone (JPL 9950-776), Tarrytown, NY, September 1982.

Critical Fluid Systems, Inc., Assessment of Critical-Fluid Extractions in the Process Industries (JPL 9950-776), Cambridge, Mass., April 1982.

Di Stefano, S., Gupta, A., and Ingham, J. D., Generation of Chemical Intermediates by Catalytic Oxidative Decarboxylation of Dilute Organic Acids (JPL Publication 83-19), Jet Propulsion Laboratory, California Institute of Technology, Pasadena, Calif., March, 1983.

England, C., Isothermal Separation Processes (JPL 9950-813), Engineering Research West, Santa Monica, Calif., July 15, 1982.

Ingham, J. D., Potential Membrane Applications to Biocatalyzed Processes: Assessment of Concentration Polarization and Membrane Fouling (JPL Publication 83-6), Jet Propulsion Laboratory, California Institute of Technology, Pasadena, Calif., November 1, 1982.

Jet Propulsion Laboratory, California Institute of Technology, Chemical Processes Project Multi-Year Research Agenda (JPL 5030-558), Pasadena, Calif., July 21, 1982.

Lonsdale, H. K., Membrane Separation Technology in the 1980s, Report No. 46-1, Bend Research Inc., Bend, Ore., March 2, 1982.

Srienc, F., Campbell, J. L., and Bailey, J. E., Detection of Bacterial ß-Galactosidase Activity in Individual Saccharomyces cereviciae Cells by Flow Cytometry, California Institute of Technology, Biotechnology Letters 5, 43(1983).

B. REFERENCES

Hopkinson, D. S., Jr., and Day, J. W., Jr., Science, Vol. 207, p. 302, 1980.

Levy, P. F., Sanderson, J. E., and Wise, D. L., Biotechnology and Bioengineering Symp. No. 11, p. 239, John Wiley and Sons, New York, 1981.

Levy, P. F., Sanderson, J. E., Ashare, E., Wise, D. L., and Molyneaux, M. S., Liquid Fuels Production from Biomass, final report to the U.S. Department of Energy, DOE/ET/20050-T1, from Dynatech Corporation, Cambridge, Mass., June 30, 1980.