FY 85 Annual Report

Systems Analysis Research for Energy Conversion and Utilization Technologies (ECUT)

November 1985

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FY 1985 Annual Report

SYSTEMS ANALYSIS RESEARCH FOR ENERGY
ENERGY CONVERSION AND UTILIZATION
TECHNOLOGIES (ECUT)

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FOREWORD

The Energy Conversion and Utilization Technologies (ECUT) Program of the U.S. Department of Energy (DOE) conducts research to increase energy conversion efficiency and to enhance the capability to use alternative, non-critical fuels. ECUT's activities ensure that a scientific and technical knowledge base is available for industrial, transportation, utility, and residential/commercial energy users, thereby supporting the U.S. commitment to advancing energy technologies. This sustained commitment is necessary if the U.S. is to continue to lead the world in technological innovation and industrial productivity.

To fulfill these objectives, ECUT positions itself at the leading edge of technology, monitors the results of basic research, and focuses this basic knowledge on problem areas that prevent using these research results in actual applications. ECUT fills the gap between basic science and engineering applications through applied research and exploratory development.

This Annual Report highlights ECUT accomplishments in the Systems Analysis Project for FY 1985. The Systems Analysis Project, conducted by the Pacific Northwest Laboratory (PNL), was established in 1980 along with the ECUT Division. The Systems Analysis mission is to identify, analyze, and assess R&D needs and research program strategies for advanced conservation technologies. The PNL Systems Analysis staff conducts topical research, provides technical studies, and plans program activities in three areas related to energy conversion and utilization technologies: 1) technology assessment, 2) engineering analysis, and 3) project evaluation and review.

This report summarizes the technical results and accomplishments of the FY 1985 projects. Section 1.0 briefly describes the ECUT Program, and Section 2.0 describes the role of the Systems Analysis Project within the ECUT Program. Section 3.0 summarizes some of the accomplishments for FY 1985. Section 4.0, the major portion of the report, highlights seven key technical tasks. Section 5.0 describes the project organization, identifies task leaders, and briefly describes the PNL project staff. The last section lists the publications resulting from the project.

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Many members of the PNL project team contributed to the preparation of this report. The following list acknowledges the individual contributions.

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1.0 THE ECUT PROGRAM

The Energy Conversion and Utilization Technologies (ECUT) Program of the U. S. Department of Energy (DOE) was started in 1980 to conduct research on advanced energy concepts that would improve energy efficiency and increase the use of alternative fuels. The ECUT Program is managed by Marvin E. Gunn, Jr., James J. Eberhardt and Terry M. Levinson at the DOE.

1.1 GOALS OF ECUT

ECUT supports longer-term, generic research on specific technical problems that inhibit the use of improved energy technologies. ECUT thus directs basic research on processes and materials to improve both the efficiency of energy components, devices, and systems and their ability to use alternative fuels.

ECUT research does not develop hardware but rather addresses specific technical deficiencies. It seeks to provide critical knowledge for the private sector to use in developing and marketing new generations of energy technologies. ECUT research also develops tools for improving productivity and efficiency, such as validated computer models, design and analytical methods, experimental data and correlations, and new measurement methods. These tools in turn lead to the development of new, innovative concepts for improved efficiency and/or alternative fuel use.

1.2 PRIORITY RESEARCH AREAS

Currently the ECUT Program conducts research in several priority areas. Figure 1.1 lists these areas and visually demonstrates ECUT's role in filling the gap between basic research and government and industrial applications. Priority research is conducted to move basic research results to application. In turn, specific research needs in industry and government are also identified and communicated to basic researchers.

To summarize, ECUT conducts generic applied research activities to:

- Understand and improve techniques, processes, and materials necessary for solving specific problems associated with energy efficiency limits and the use of alternative fuels

FIGURE 1.1 The Role of ECUT Priority Research in Filling the Gap in Technology Transfer

- Monitor and evaluate advances in basic scientific research for possible application to energy conversion technologies
- Conduct exploratory development of novel, innovative conservation concepts
- Establish the feasibility of concepts that offer the potential to significantly reduce energy consumption
- Transfer information on conservation-related technical advances to DOE end-use sector conservation programs and to private industry.

The following sections describe specific ECUT research activities in the various priority research areas.

1.2.1 Combustion and Thermal Sciences

Combustion Research. Multidimensional calculations and laser-based diagnostic techniques are developed and used to improve understanding of combustion and combustion-related processes in intermittent and continuous combustion systems.

Thermal Sciences Research. Analytical and experimental techniques are developed and applied to improve understanding of the thermodynamics, heat and mass transfer, and fluid mechanics of processes fundamental to efficient, reliable energy conversion components and systems.

1.2.2 Materials

High-Temperature Materials. Research is conducted in two areas: metallic materials and ceramics. This research is conducted to develop metallic materials of ordered crystal structure useful to the design of future high-performance steam turbines, heat engines and heat exchangers. In the ceramics area, a main objective is to improve understanding of the problems and limitations inherent in using ceramics in advanced energy conversion applications.

Materials-by-Design. Research in this area focuses on understanding the relationship of desired properties (e.g., ductility) and performance characteristics (e.g., high temperature survivability) to the structure and bonding in materials. Structural and bonding models are developed to predict the performance of any given assembly of atoms or molecules.

Lightweight Materials. Composite materials and corrosion-resistant magnesium alloys are developed for ground transportation applications. Work also includes investigating ways to reuse post-consumer plastics to recover large quantities of high-energy content waste materials.

1.2.3 Biocatalysis

Molecular Modeling and Applied Genetics. The main objective of these efforts is to establish molecular structure criteria to be used by industry in selecting an optimum catalyst for any specified chemical reaction.

Bioprocess Engineering. Representative biocatalyzed reactions are investigated to determine immobilizing techniques and reaction conditions under which the catalytic activity of recombinant-DNA produced enzymes can be maintained; these findings are then correlated to the enzyme structure.

Process Design and Analysis. Plant engineering design tools and a process technology base are developed for scaling up bioprocesses to the pilot plant stage.

1.2.4 Tribology

Lubricants. Particular molecular types and structures in lubricating base stock oils are identified that influence friction and wear. Bench-scale

standardized test procedures are formulated that can replace cumbersome and expensive heuristic tests.

Tribological Coatings. Surface modification techniques are utilized to reduce friction and wear between moving surfaces. Tribological systems that function without liquid lubricants are also being developed.

1.2.5 Innovations

In this area innovative ideas and concepts in the initial research stages are sought, encouraged and supported. Rapid transfer of these research concepts to DOE end-use sector conservation programs and/or to private industry complements this effort.

1.3 THE ECUT APPROACH

ECUT conducts research through cooperative efforts involving private and federally-funded laboratories, the universities, and industry. This cooperative approach provides interdisciplinary review of technology needs and problem definition. In addition, the ECUT program facilitates the transfer of research results to the technology users.

Major contributions to ECUT activities are made by the Albuquerque Operations Office, Sandia National Laboratory, Argonne National Laboratory, the Jet Propulsion Laboratory, Idaho Operations Office, Oak Ridge National Laboratory, and Pacific Northwest Laboratory. Although ECUT activities are long-term, results produced in the interim are also directly applicable to nearer-term energy conservation technology programs. As a division in the Office of Conservation, ECUT seeks to directly transfer these interim R&D results to the more development-oriented work supported by the conservation end-use programs.

2.0 THE ECUT SYSTEMS ANALYSIS PROJECT

The Systems Analysis Project is an integral part of the ECUT Program. This section describes the goals, objectives and rationale for the project.

2.1 SYSTEMS ANALYSIS PROJECT OBJECTIVES

The Systems Analysis Project was established in 1980 to provide the ECUT Program with a strong technical foundation for its program planning and laboratory research activities. PNL has defined its overall Systems Analysis Project goal as:

"To develop and execute methodologies to provide technical assessment and planning information on ECUT technologies for the design, operation, and evaluation of advanced energy technology R&D programs."

The following project objectives were chosen because they provide key planning and coordination information needed by the ECUT Program. Each Systems Analysis task is designed to meet one or more of these objectives:

- to identify research needs for advanced energy conversion technologies
- to conduct independent technical reviews of ECUT technology areas to focus research on high priority problems
- to evaluate innovative developments or cross-cutting technologies of interest to ECUT to assess the need for federal support
- to analyze the benefits of ECUT research to assess overall program impact
- to study and develop conservation analysis methodologies
- to monitor advances in basic science that represent opportunities to advance state-of-the-art energy conversion and utilization
- to assist in the timely transfer of ECUT research results to user groups in government and industry.

The Systems Analysis Project staff fulfills critical needs for ECUT by identifying and assessing technical barriers, evaluating and prioritizing

research opportunities, evaluating the benefits of ECUT research activities, and facilitating the transfer of ECUT research findings to potential users. The benefits from these efforts include:

- Credible technology planning and analysis methods that are developed for the program
- Independent technical reviews on specific technical topics that provide a check on the nature and direction of the projects advocated by the ECUT research laboratories
- Data and reports that evaluate and justify ongoing and future ECUT research programs for program planning and evaluation
- Systems analysis activities that give the various research laboratories, e. g., Sandia, Oak Ridge, perspective on how their work contributes to the ECUT Program
- Communication of ECUT research to a wide range of potential users who might not otherwise be reached.

2.2 THE SYSTEM ANALYSIS PROJECT APPROACH

As shown in Figure 2.1, PNL staff work directly with ECUT Program Managers and the ECUT Field Managers (such as Dr. Joseph Carpenter, Manager of the ECUT Materials Project at Oak Ridge National Laboratory) to provide technical, analytical, and strategic planning support. This support is provided in three significant ways: 1) by developing systems analysis research methods for ECUT use, 2) by conducting cross-cutting studies that involve all ECUT priority research areas, and 3) by conducting systems analysis research in ECUT priority research areas. These three categories are described in detail below.

Systems Analysis Research Methods

Systems analysis methods are developed for specific application to ECUT. Just as the Combustion Project requires the latest and best available instrumentation, the Systems Analysis Project needs improved, credible methods to conduct its research. These methods include approaches for the evaluation

FIGURE 2.1. ECUT Program Organization

of energy conversion technologies and alternative fuels. Improved techniques for group decision making, analysis and planning are also needed. In addition, computer software for program evaluation activities can be extremely helpful. These tools increase the accuracy and credibility of ECUT decisions regarding project funding, duration and relative importance to ECUT. Some recent examples of this type of research are listed below:

- The method for the Research Appraisal/Technology Evaluation (RATE) project appraisal that was designed and first implemented at the ECUT Managers' meeting in June, 1985.
- The methods for evaluating the benefits of ECUT research activities that are currently being developed and evaluated; recommendations for specific applications resulting from this effort will be made during FY 1986.
- The irreversibility analysis method that is currently being used in the Regenerative Heat Exchanger Systems Analysis task. This technique evaluates the energy efficiency of systems relative to a thermodynamic ideal.

Cross-Cutting Research

Cross-cutting research studies are ongoing activities that cut across all of the ECUT priority research areas. These systems analysis activities are essential in evaluating potential benefits of research and deciding which

projects should be selected. Typical activities of this type include 1) appraisal of existing research projects, 2) evaluation of research program outputs, 3) monitoring basic research outputs, and 4) facilitating the transfer of ECUT technology. The current RATE activity mentioned above is an example of the type of cross-cutting research project that should be conducted on an ongoing basis.

Priority Research Areas

Systems analysis research in specific priority research areas (such as thermal sciences and tribology) is an essential element of the project. Examples of the work conducted in these areas include technical assessments, feasibility studies, R&D needs assessments, program planning support, studies of basic principles and theoretical calculations, and surveys of foreign technology, approaches and experience. This type of work directly supports specific research topics at the field laboratories. For the past two years, the majority of the Systems Analysis Project efforts has been directed into this type of research. Specific research has included:

- Laser diagnostic capabilities and applications
- Opportunities for increased efficiency using pulse combustion
- Energy conservation opportunities through biotechnology
- Energy and economic savings from improved catalysts
- Tribological sinks in six major industries.

Ongoing Systems Analysis work in the priority research areas is critical because it keeps PNL staff in day-to-day contact with these areas and facilitates effective working relationships with the field laboratories. Furthermore, through these efforts PNL staff can gauge technical problems and how they are being addressed by laboratory researchers.

3.0 ACCOMPLISHMENTS IN FY 1985 FOR THE ECUT SYSTEMS ANALYSIS PROJECT

The Systems Analysis Project accomplished a number of objectives and milestones in FY 1985 that contributed substantially to the ECUT Program. Significant accomplishments were achieved in support of ECUT Headquarters planning and in support of all the major ECUT Technical Program areas, including energy conversion, materials and tribology. These accomplishments are listed below:

- Designed and initiated a method to evaluate 22 projects currently being conducted by ECUT. This process, Research Appraisal/Technology Evaluation (RATE), which involves both headquarters and field operations staff, will be completed during FY 1986.
- Conducted a study to identify, evaluate and recommend techniques to quantify the benefits of ECUT research program activities. Case studies of selected ECUT outputs were used to help define a strategy for effective benefit evaluation.
- Completed the six-volume ECUT Tribology Research Series. These reports represent a cornerstone effort to evaluate the nature of tribological problems, specify research needs, and assess the effectiveness of current government tribology research programs.
- Initiated a study with the National Academy of Sciences to evaluate using bioprocessing for energy-efficient production of bulk chemicals and acted as technical liaison for all NAS meetings to represent ECUT's perspectives. The final report will be issued in April, 1986.
- Completed a study on tribological needs in the emerging industries of electronics and robotics. The final report will be issued in FY 1986.
- Conducted a study to estimate the potential energy savings and economic impacts of applying materials-by-design technology to the development of ideal catalysts. This "landmark" study will be published as a DOE document in FY 1986.

- Continued follow-up work on identifying research needs and potential applications for pulse combustion technology and published a report entitled "Opportunities in Pulse Combustion."
- Initiated a study to examine fundamental loss mechanisms in heat engine regenerators. The results of this technical analysis will be used to provide guidance for ANL research.
- Published popular tribology document entitled "Tribological Sinks--Money Down the Drain." This document summarizes the results of six ECUT studies conducted in various aspects of tribology.
- Hosted Annual ECUT Managers' Meeting in Washington, D.C. Made all plans for facilities and logistics.
- Developed the new ECUT graphic to portray how ECUT research fills the gap between basic research and application in government and industry.
- Developed capabilities in using the "Storyboarding System" for research planning.

4.0 PROJECT FEATURES

This section features several research tasks conducted under PNL's System Analysis Project in FY 1985. The descriptions summarize the purpose and objectives, project staff, findings, and results, and conclusions and recommendations for each of these projects:

- The ECUT Tribology Series
- Energy and Economic Savings from Improved Catalysts
- ECUT Benefit Measurement Techniques
- Regenerative Heat Exchanger Systems Analysis
- Tribological Sinks in Emerging Industries: Robotics and Electronics
- Research Appraisal/Technology Evaluation (RATE)
- Bioprocessing for the Production of Bulk Chemicals.

4.1 PROJECT FEATURE: ECUT TRIBOLOGY SERIES

PROJECT STAFF: J. A. Russell, C. H. Imhoff, D. C. Debrodt, J. E. Danko, V. E. Lee.

4.1.1 Introduction

Experts have estimated that in 1978 alone over four quadrillion Btu of energy were lost because of simple friction and wear. This translated into a \$20 billion loss, based on 1978 oil prices of \$30 per barrel. Because of the enormity of this loss, in 1983 ECUT initiated a program to identify and characterize these tribological losses or sinks. To support initial planning for this ECUT Tribology Program, ECUT sponsored six surveys to gather three types of information about the current tribological loss problem in U.S. industries:

1. The identification of typical industrial sinks
2. A survey of current U.S. Government tribology research projects
3. The identification of tribology R&D needs based on industry perceptions.

The six surveys listed in Table 4.1 were thus conducted to provide this information. These surveys were made during FY 1984, and the results finalized

TABLE 4.1. ECUT Tribology Surveys

1. A Review of Tribological Sinks in Six Major Industries. Imhoff, et al. PNL-5535, Pacific Northwest Laboratory, Richland, Washington.
2. Reduction in Tribological Energy Losses in the Transportation and Electric Utilities Sectors. Pinkus and Wilcock, Mechanical Technology Incorporated. PNL-5536, Pacific Northwest Laboratory, Richland, Washington.
3. Identification of Tribological Research and Development Needs for Lubrication of Advanced Heat Engines. Fehrenbacher, Technology Assessment and Transfer, Incorporated. PNL-5537, Pacific Northwest Laboratory, Richland, Washington.
4. Energy Conservation Potential of Surface Modification Technologies. Le, DHR, Inc. PNL-5538, Pacific Northwest Laboratory, Richland, Washington.
5. Assessment of Government Tribology Programs. Peterson, Wear Sciences Corporation. PNL-5539, Pacific Northwest Laboratory, Richland, Washington.
6. Assessment of Industrial Attitudes Toward Generic Research Needs in Tribology. Sibley and Zlotnick, Tribology Consultants Incorporated. PNL-5540, Pacific Northwest Laboratory, Richland, Washington.

during the first part of this year. A summarizing document, entitled "Tribological Sinks--Money Down the Drain," was prepared by the Systems Analysis Project staff in January. During the remainder of the fiscal year, PNL published the six ECUT surveys as a series.

4.1.2 Results

The results from these six surveys, categorized by the three types of information described above, are summarized in the following sections.

Identifying Typical Industrial Sinks

ECUT's first step in collecting information on tribology was to identify significant tribological sinks and mechanisms. Because the industry, transportation, and utilities sectors account for most of the energy consumed in the U.S., the survey concentrated on the tribological sinks and mechanisms found in these sectors. The report by Imhoff, et al., describes the most significant tribological sinks in industry, and the report by Pinkus and Wilcock describes tribological energy losses in the transportation and utilities sectors. Two

more specific studies of tribological sinks in the metalworking industry and in advanced diesel engines were conducted by Le and Fehrenbacher, respectively.

For the industrial sector, the results confirmed earlier claims that energy losses caused by material wear are greater than those caused by friction. The frictional energy losses in five representative industries (Mining, Agriculture, Primary Metals, Chemicals/Refining, Pulp and Paper, and Food Processing) were found to be more than twice as large as wear losses (see Figure 4.1). The study also concluded that reducing material wear to prolong equipment life could significantly improve productivity.

For the metalworking industry, the Le study estimated the energy conservation potential of using surface modification technologies to reduce friction and wear in equipment typically used in this industry. The author estimated that friction losses in all U.S. metalworking machines are about 20.2×10^{12} Btu per year. Of this loss, about 1.8×10^{12} Btu per year, or about 9%, could

FIGURE 4.1. Annual Friction and Wear Losses in Surveyed Industries

be saved using surface modification technologies to reduce friction. The wear loss was estimated to be 7.7×10^{12} Btu per year, of which about 5.5×10^{12} , or 71%, could be saved using these technologies.

The Pinkus and Wilcock study identified tribological energy losses in the transportation sector. The principal automotive energy sinks are caused by friction. Tribological improvements in this sector (particularly in the piston/ring assembly and reducing engine wear) could save 18.6% of the total annual energy consumed by automobiles.

Because advanced engine technologies have the potential to reduce energy consumption; the Fehrenbacher study examined the tribological problems with these engines. The study concluded that advanced diesel concepts will require new design approaches, and that the tribology of the upper cylinder region will be critical and may even constitute the major technological barrier to achieving higher engine efficiencies.

The utilities sector accounts for roughly 28% of total U.S. energy consumption. ECUT's review of this sector concluded that tribological improvements in efficiency and reliability could save 2.3% of this total. As in the transportation sector, friction is the major factor.

Current Government Tribology R&D Projects

The Peterson study identified tribology R&D projects currently being sponsored or conducted by the U.S. government. This information was needed to avoid duplicating research and to locate areas requiring more research support. The study identified 215 current projects sponsored by 21 different government organizations. The major government sponsors include the Department of Defense, the National Aeronautics and Space Administration, the National Science Foundation, and the National Bureau of Standards. High-temperature lubrication, coatings, and basic understanding of friction, wear, materials, and coatings are the research areas receiving the most attention.

Industry Perceptions of Tribology Research Needs

Because transferring technical information to industry is a major part of the ECUT program, ECUT conducted a survey of industry perspectives on tribology

R&D needs. This survey, conducted by Sibley and Zlotnick, involved in-depth discussions with engineers and managers from 27 companies.

The authors concluded that industry conducts only a very limited amount of generic tribology research. The industry representatives interviewed expressed interest in improving the fundamental understanding of tribological mechanisms, and also requested more effective information transfer of research results and more realistic laboratory tests and performance standards.

4.1.3 Recommendations

The five key results from the six studies in the ECUT Tribology Series are listed below.

1. Advanced tribo-materials, coatings and lubricants must be developed to improve engine efficiency.
2. Tribological mechanisms that shorten equipment life and cause excessive downtime and repair should be identified and studied. These indirect energy losses from material wear are often far greater than the direct energy losses from friction, and thus reducing these energy losses could also significantly improve industrial productivity.
3. Generic tribological research results must be effectively transferred to all three major sectors, industry, transportation, and the utilities, since similar tribological mechanisms are found in many different processes.
4. Meaningful performance tests and standards must be developed so that new designs and products can be accurately evaluated. Laboratory tests that reflect real-world conditions and total system testing are particularly important.
5. Communicating with industry is critical to ensure that industry R&D needs are met and that research results are effectively transferred.

4.2 PROJECT FEATURE: ENERGY AND ECONOMIC SAVINGS FROM IMPROVED CATALYSTS

PROJECT STAFF: D. L. Brenchley, E. A. Griffin, D. R. Johnson,
A. J. Lezburg, S. E. Lyke, J. A. Russell, J. K. Young.

4.2.1 Introduction

Improvements in the technology of catalyst materials can have a major impact on the energy consumed in processing fuels and chemicals. Catalysts also are of particular interest because the current American industrial preeminence is being challenged by Japan, West Germany and France. Materials technology has advanced significantly in recent years. If progress in this area continues, catalysts could be designed that would have a major positive impact on the national and world energy situation. This study estimated the energy and economic benefits of applying the materials-by-design concept to catalysts.

In this study the potential economic and energy impacts of introducing ideal catalysts (i.e., optimal with respect to conversion efficiency and regeneration) were assessed by using three case studies: fluid catalytic cracking, alkylation and styrene production. These cases were selected because they are typical of large scale catalytic processing in using large amounts of energy; these processes, therefore, could maximize the benefit from the development of improved catalysts. The benefits were estimated by comparing current capital and operating costs and energy uses with processes using the optimally designed catalysts. National impacts were then estimated for these case study industries. In addition to these quantitative estimates, important qualitative descriptions were developed that define the importance of improved catalysts in promoting feedstock flexibility in industry and other benefits, such as environmental control.

4.2.2 Results

The results from this study in terms of potential energy savings, capital and operating cost savings, and potential national impacts are described below.

Potential Energy Savings

Fluid catalytic cracking, alkylation and styrene production are energy-intensive processes. In all these cases the use of ideal catalysts would provide opportunities for savings in feedstock energy and process energy.

Fluid Catalytic Cracking (FCC). Catalytic cracking breaks down high molecular weight hydrocarbons from heavy petroleum fractions to lighter compounds, such as gasoline. About one third of the total input to a refinery is processed by catalytic cracking, making it second only to hydrotreating as the largest catalytic refining operation in terms of process volume. Total energy consumption for the state-of-the-art FCC, including feedstock energy and all utility requirements, is currently 2.8×10^6 Btu/bbl feedstock, or 2.12×10^4 Btu/lb gasoline produced.

The amount of energy that could be saved by using an ideal catalyst is estimated to be 1.3×10^3 Btu/lb of gasoline produced. The energy savings would result from reduced feedstock requirements, which would be cut in half while still yielding the same volume of gasoline. No process energy savings are expected, but feedstock energy savings would be significant. Total gasoline production was 6.5×10^6 bbl/dy in 1984, of which 1.86×10^6 bbl/dy were produced by FCC. Assuming 100% market penetration, the amount of feedstock energy that could be saved is 2.57×10^{14} Btu/yr.

Alkylation. Alkylation reactions combine mixed butylenes and/or propylenes with isobutane to form highly-branched, high-octane enhancers for gasoline. Process volume is smaller relative to other refining operations, but process energy consumption is relatively high. Total energy consumption for the state-of-the-art alkylation process is currently 2.052×10^4 Btu/lb alkylate produced. This total includes feedstock and production energy, and all utility requirements.

The amount of energy that could be saved by using an ideal catalyst is estimated to be 950 Btu/lb alkylate produced. Feedstock requirements would be unchanged, but process energy requirements could be reduced by 85%. Since production of alkylate was 5.89×10^5 bbl/dy in 1982, the amount of process energy that could be saved is 4.85×10^{13} Btu/yr, assuming 100% market penetration.

Styrene Production. If ideal catalysts were employed to produce styrene from coal-derived synthesis gas, the total energy requirements could be reduced by about 10%. For current annual styrene production, this represents a

potential savings of 3.3×10^{13} Btu/yr. In addition, the energy used would be from coal, an abundant feedstock, rather than from petroleum-derived ethylene and benzene.

Potential Savings in Capital and Operating Costs

The capital and operating cost savings resulting from substituting ideal catalysts for fluid catalytic cracking, alkylation, and styrene production are summarized below. In all three cases, over half of the capital costs of a new plant could be saved.

Fluid Catalytic Cracking (FCC). Capital cost for a new state-of-the-art FCC unit producing 19,950 bbl/dy of gasoline is reported to be \$67 million in 1983 dollars. If an ideal catalyst were used, requirements for flue gas cleanup, fractionation, and regeneration would not be as rigorous, and therefore capital costs could be dramatically lower. Capital costs for a new FCC unit incorporating an ideal catalyst would be only half the state-of-the-art FCC unit, or \$34 million in 1983 dollars.

Alkylation. Capital cost for a new state-of-the-art alkylation unit producing 3500 bbl/dy of alkylate is reported to be \$9.5 million in 1983 dollars. Alkylation units are currently of two types, using either HF or H_2SO_4 as a catalyst. Capital costs are equivalent for each type. If an ideal catalyst were used, requirements for acid circulation and cleanup would be eliminated, refrigeration requirements would be greatly reduced, and heating requirements would be somewhat reduced. Capital costs for an alkylation unit that incorporated the ideal catalyst would be 44% of the state-of-the-art alkylation unit, or \$4.2 million in 1983 dollars. Operating cost savings would equal \$3.00/bbl alkylate.

Styrene Production. Capital costs for an ideal styrene process are about 90% less than the costs of a conventional plant. Savings result from: 1) increased throughput, 2) plant simplicity, and 3) milder operating conditions required for an "ideal" catalyst.

Operating costs for a plant producing styrene from synthesis gas are about 2% more than the costs for existing plants using conventional technology. This is because feedstock costs are actually higher, based on existing economic

conditions. However, advances in coal gasification technology and potential increases in crude oil prices could substantially reduce the price of synthesis gas relative to benzene and ethylene.

Cumulative National Impacts: 1985-2000

Data for Standard Industry Classifications (SICs) were used as a basis for estimating the cumulative impacts of ideal catalysts. The time frame used for this assessment, 1985 to 2000, is merely illustrative. The research needed to provide catalyst design capability actually would take a significant portion of this time period.

Feedstock Energy Savings. For organic chemical production an estimated 1.1 quads (1 quad is 10^{15} Btu) could be saved and for petroleum refining 7.9 quads could be saved. This is a total of 9 quads out of a total of 511 quads used.

Process Energy Savings. An estimated 6.6×10^{14} Btu could be saved in organic chemical production, but an increase of 1.15×10^{15} Btu for petroleum refining would be realized. This increase is due to the greater weight placed on petroleum refining by the methodology used in this study; process energy savings were forfeited to attain larger feedstock energy and capital cost savings.

Capital Cost Savings. A cumulative total of about \$193 billion will be invested between 1985 and 2000: \$76 billion for the organic chemicals industry and \$117 billion for the petroleum refining industry. If ideal catalysts were available, capital cost savings of \$15.4 billion for organic chemicals production and \$16.7 billion for petroleum refining could be realized.

Operating Cost Savings. Because of an overwhelming dependence on the costs of feedstocks, the estimates of operating cost savings bear much resemblance to the estimates of feedstock energy savings. Presumably all the products on the national slate could be produced more efficiently and cheaply. However, since all the products of the case study refinery are demanded in the marketplace, it is assumed that feedstock will be required to produce them. Given these caveats, industry-level operating costs are expected to increase \$9.8 billion. This increase is due to an estimated \$6.4 billion decrease in

petroleum refining offset by an estimated \$16.2 billion increase for organic chemicals. The reason for the \$16.2 billion increase is that the production of synthesis gas from coal is estimated to be more expensive than the production of ethylene and benzene feedstocks from petroleum.

Additional Benefits of Improved Catalysts

There are several very large potential benefits that were not addressed in the case study calculations. These additional benefits further support the rationale for developing materials design technology for catalysts. Some of these potential benefits are described below.

Reduced Environmental Impacts. The volume and content of pollutant byproduct streams could be minimized. Use of improved catalysts could reduce toxic wastes and emissions that contribute to problems such as acid rain.

Greater Use of Alternative Feedstocks. One of the most strategically significant benefits that could result from development of a catalyst design capability would be the use of less expensive, more abundant domestic resources such as coal and biomass for fuel and petrochemical production. A decrease in U.S. dependency on foreign imports of petroleum also would be a highly desirable benefit.

Development of New Chemicals and Process. The availability of ideal catalysts would spur the development of new processes. For example, improved catalysts could play a key role in the development of technology to produce hydrogen from waste materials by the photolysis process. Use of this technology would result in a clean burning fuel that does not produce air pollutants.

4.2.3 Recommendation

The question is whether there is a sufficient payoff to warrant the research investment needed to commercialize the materials-by-design approach. Initial estimates developed in this study reveal a potential capital cost savings of \$30 billion for chemical and petroleum refining plants over a 15-year period. This study substantiates the need for a major U.S. effort to enhance materials-by-design technology for catalyst materials to ensure preeminence by U.S. industry. However, another conclusion from this study is that the case study involving producing styrene from coal-derived synthesis gas introduces

too many unknowns into the analysis (i.e., the cost of synthesis gas). The case study will be re-evaluated in FY 1986, using ethylene and benzene as feedstocks. This will result in a more direct comparison between the existing method and the ideal method.

Another approach may be to examine the development of a catalyst that produces complex chemicals directly from coal without destroying its complex molecular structure. In contrast, the case study involving production of styrene from synthesis gas is based on the conversion of coal to simple molecules (CO and H₂) and the catalytic conversion of these molecules to the complex styrene molecule.

4.3 PROJECT FEATURE: ECUT BENEFIT MEASUREMENT TECHNIQUES

PROJECT STAFF: L. O. Levine and C. Winter.

4.3.1 Introduction

This project was conducted to define and develop techniques that could be used to measure and describe the complete spectrum of positive effects resulting from ECUT Program activities. Increased understanding of the results of previously sponsored research would strengthen ECUT research utilization and research planning.

In this study, an approach for evaluating ECUT benefits was developed. First, literature on R&D benefit evaluation, scientific communication and technical information transfer was reviewed. From the literature review, an evaluation strategy was developed based on the concept of measuring program output impact. Techniques for implementing this strategy were proposed, and data base managements needs for the evaluation were examined. A list of ECUT-funded research outputs for the period 1976-1983 was compiled as a parallel activity. (Selected outputs published in 1984 were included in this list.)

A key part of this project was determining whether techniques could be found to cost-effectively identify a significant share of the "ultimate" users of the outputs of ECUT-sponsored research so that these users could be contacted and surveyed concerning research utilization. To explore this issue,

outputs from three research areas were selected from the list of ECUT outputs and used as case studies. The research areas and outputs used are listed below:

1. Combustion Research -

CONCHAS-SPRAY: A Computer Code for Reactive Flows with Fuel Sprays. May 1982. Los Alamos Laboratory Report LA-9294-MS.

2. Materials -

- a. "Physical Metallurgical and Mechanical Properties of Ductile Ordered Alloys (Fe, Co, Ni)₃V." 1984. International Metals Review 29:(3)168-194.
- b. Development and Characterization of Ductile Long-Range Ordered (LRO) Alloys (Fe, Co, Ni)₃V for High-Temperature Structural Use. August 1984. Oak Ridge National Laboratory Report ORNL-6032.

3. Tribology -

- a. "Relationship Between Lubricating Basestock Composition and the Effects of Additives on Oxidation Stability." 1982. SAE Reprint 821237.
- b. Ku, C. S. and S. M. Hsu. 1982. "Thin-Film Oxygen Uptake Test for the Evaluation of Automotive Crankcase Lubricants." ASLE No. 82K-LC-1D-1, presented as an American Society of Lubrication Engineers (ASLE) paper at the ASME/ASLE Lubrication Conference, October 5-7, 1982, Washington, D.C. Also published in Lubrication Engineering 40:(2) :75-83.

In addition to the three case studies, two other types of data were analyzed. First, order information for 38 technical reports was obtained in the NTIS system. These data were examined to clarify the usefulness of order requests in identifying users of published ECUT research results. Second, a small survey of combustion researchers was conducted to sample the research community's awareness of ECUT-funded work and to identify the dominant mechanisms of information transfer.

4.3.2 Results

The literature review raised several issues to be addressed when evaluating the benefits of ECUT program outputs. These issues are listed below:

- There is frequently a long "gestation" period between research outputs and technological innovations.
- The utilization of scientific and technical information is a non-linear, complex process, which makes it difficult to evaluate the importance of different information inputs.
- Scientists and engineers have very different patterns of information utilization. Therefore, the type of document and ultimate user must be considered in evaluating benefits.
- Measuring economic benefits, either direct or indirect (i.e., spin-offs), requires detailed economic information on a case-by-case basis. Even so, research with potentially large benefits may be underestimated when first completed.
- Bibliometric methods measure the impact of a particular research output; this impact is a function of quality, relevance to current needs, and success of information transfer. Bibliometric methods measure impact at a given point in time.

To address these issues, the suggested approach was based on the idea that measuring the effects of ECUT efforts should focus on the impact of specific ECUT program outputs. "Impact" of a program output refers to its actual influence on R&D activities at a given point in time.

A variety of techniques to identify the utilization of specific ECUT outputs was suggested. First, bibliometric methods could be used to analyze the impacts represented by citations to journal publications, requests for article reprints, and requests for technical reports from the National Technical Information Service (NTIS). The citation and reprint data would also identify users of ECUT outputs. When these users were identified, they could be surveyed to gain further insight into the extent of the impact of ECUT outputs.

This approach suggests the need for a fairly complex data base management system. A review of commercially available software indicated that a data base management system developed with the Pascal programming language could fulfill the functional requirements of implementing this approach.

Request information for 38 ECUT documents supplied by NTIS was analyzed. Requests were broken into three categories. The first category included libraries, information acquisition departments, and information scientists, all of whom were presumably ordering for someone else. A second category consisted of individuals, either with or without company affiliation, who did not appear to fall in the first category. The last category consisted of other organizations (companies, embassies, etc.) with no individual specified.

Table 4.2 reveals that about 70% of the requests were from unnamed individuals or from individuals requesting the document for another person. Since one-half of the individual requests were for documents dealing with technology planning (e.g., conservation research opportunities) only about 15% of the total requests might have come from users interested in the results of technical research funded by ECUT. Therefore, if surveys are limited to known users (Category 2), the overall response rate will be low. The alternative is to conduct a difficult and time-consuming attempt to identify the users initiating NTIS requests in the other two categories.

A survey was developed that consisted of a form listing publications and presentations of ECUT-sponsored combustion research which asked whether the researcher was familiar with the research output. If so, the survey respondent was asked if he or she was aware that ECUT had funded the research. A small

TABLE 4.2. NTIS Requester Profile

<u>Research Area</u>	<u>Library or Information Specialist</u>	<u>Individual Requester</u>	<u>Other Organizational Request</u>
Engine Combustion	38	14	16
Thermal Science	25	8	3
Closed-Cycle Systems	29	15	5
Direct Heat and Conversion	8	2	4
Materials	2	2	2
Technical Planning	52	44	18
TOTAL	154	85	48
PERCENT	53.7%	29.6%	16.7%

number of combustion researchers were surveyed and the results are shown in Table 4.3. In cases where the research output was known, over four-fifths of the responses indicated no awareness of ECUT funding (one respondent noted that he was unaware of ECUT's role in producing a document, but that NSF funding had been acknowledged). The survey results also suggest that technical journal or society paper publications and presentations at conferences accounted for at least two-thirds of the information transfer for these researchers.

The key findings from the case studies are listed below:

- Technical reports are not likely to be referenced in the refereed literature. Thus, indications of research utilization in technical reports are limited to requests for copies (from NTIS, authors, and ECUT) and distribution lists.
- Requests for documents can be identified through NTIS. Request information from professional societies is more limited. However, information on the ultimate users of these requests is difficult to obtain from either source.
- Researchers themselves provide a great deal of information transfer, by responding to requests for reprints, software, samples, etc. However, they are generally unable to provide detailed information on the requests received.

4.3.3 Recommendations

Benefits evaluation should stress identifying specific users of ECUT-funded research. Bibliometric indicators (e.g., number of articles, citations, requests for documents/reprints) by themselves do not provide an adequate basis

TABLE 4.3. Awareness of ECUT Funding for Combustion Research

Were You Aware That This Research Received ECUT Funding?

	<u>Yes</u>	<u>No</u>	<u>Total Responses</u>
Count	15	74	89
Percent	16.9%	83.1%	100%

for measuring the benefits of a program as diverse as ECUT. However, a meaningful evaluation of the benefits can be made through combining bibliometric techniques with knowledge gained from specific users of ECUT outputs identified through referencing articles and/or surveys.

User-specific information from public and quasi-public sources (e.g., NTIS, Science Citation Index, professional societies and journals) is limited and will not by itself provide a cost-effective mechanism for identifying ECUT beneficiaries. As an alternative, greater emphasis should be placed on requests made directly to the researchers. Based on the results from this project, ECUT-funded researchers probably would find a request for user information burdensome since it is unlikely that they have complete and organized records of such requests. Therefore, in order to permit cost-effective surveying of future users of ECUT research output, a reporting system should be implemented that would allow the researcher receiving the request to notify ECUT.

The recommendations can be summarized as follows:

1. A standardized reporting system should be instituted that ECUT-funded researchers could use to record requests for specific article reprints, conference papers, software, samples, etc., so that future users of ECUT outputs could be more easily identified.
2. The list of past ECUT publications should be revised to include complete bibliographic information to increase the accuracy and efficiency of searching the Science Citation Index for articles that reference ECUT-sponsored publications.
3. Researchers should be encouraged to transfer the results of their work via journal articles and conference papers and should be required to acknowledge ECUT funding.
4. A more detailed analysis of the influence of ECUT outputs should be undertaken only after the first three recommendations have been implemented and evaluated.

4.4 PROJECT FEATURE: REGENERATIVE HEAT EXCHANGER SYSTEMS ANALYSIS

PROJECT STAFF: R. A. Hutchinson and S. E. Lyke

4.4.1 Introduction

Regenerative heat exchangers use the thermal capacity of a solid matrix to store heat extracted from fluid streams passing through the matrix. The heat is then given up to a second stream passing through in either the same or the opposite direction. Even in their simplest configurations these devices are very difficult to analyze because the variation of the matrix temperature over time is hard to predict. In more complicated situations complete understanding has so far proved impossible.

Perhaps the most complicated regenerator application is the Stirling engine, a closed cycle heat engine in which working gas temperature and pressure vary constantly over the cycle. Originated in the early 19th century, the significance of this invention was not recognized for over a century, and is still not completely understood. Today's state-of-the-art analyses show that regenerators are the major source of flow friction (causing power losses) in operating engines, and transfer an order of magnitude more heat than other heat exchangers in the engine. Uncertainty about these effects poses significant problems for engineers analyzing and designing Stirling engines, which have well-documented potentials for energy conservation and fuel switching.

The uncertainty about what is occurring in a functioning Stirling regenerator stems from the impossibility of either watching or calculating what is happening. Considerable experimental and analytical efforts have been made, but no comprehensive design tools have emerged. Several proprietary design codes do appear to work well on particular classes of complete Stirling machines. However, possibly large regimes exist where no current approaches or correlations will yield realistic results.

The purpose of this task is to provide a framework for examining basic processes involved in regenerator operation. Such a framework would serve as a template for planning research projects on Stirling regenerators.

To accomplish this purpose, the approach has involved both a detailed review of the literature and an independent analysis effort. Although the

literature is sparse and scattered, allusions to problems with regenerators appear regularly. In addition, references appear from heat transfer researchers studying oscillating flows in various contexts. The analysis effort has been conducted as much to focus thinking on the inherent difficulties of calculating regenerator behavior as to provide numerical results. A fundamental loss analysis technique, irreversibility analysis, was used because it makes the dependence of results on simplistic assumptions far more obvious and also facilitates thinking about the fundamental processes involved.

4.4.2 Irreversibility Analysis

Irreversibility analysis is widely used in evaluating the energy efficiency of systems relative to a thermodynamic ideal. It stems from a formulation of the second law of thermodynamics: the capacity of a system to perform useful work is reduced by the product of the entropy generated (ΔS) in the system and the minimum temperature (T_0) at which it can reject heat. If this reduced capacity is termed "lost work" (LW), it can be written as:

$$LW = T_0 \Delta S$$

For example, if a heat engine takes in heat (Q) at T_H and simply transfers it to T_0 without producing any work, the lost work would be:

$$LW = T_0 \left(\frac{Q}{T_0} - \frac{Q}{T_H} \right) = Q \left(\frac{T_H - T_0}{T_H} \right)$$

or the full amount of work the engine could have produced operating at Carnot cycle efficiency.

The utility of the lost work concept derives from the fact that entropy generated in a system can be resolved to any degree of detail in time and space, limited only by the level of understanding of the system. Discrete entropy-generating processes, called irreversibilities, thus can be identified and their effect on system performance calculated directly.

Application of irreversibility analysis to Stirling regenerators has led to the development of a simple computer model. An isothermal analysis provides

mass flow and pressure estimates to a loss calculation spreadsheet. Losses are calculated using fluid properties, pressure drop and heat transfer correlations. The effect of different correlations on calculated engine performance or, conversely, potential refinement of correlations with experimental data can be investigated. With some refinement of the model, the effect of fluid-regenerator heat transfer resistance could be separated from that of axial dispersion and the potential benefits of advanced concepts, such as anisotropic materials or novel working fluids, could be evaluated.

4.4.3 Preliminary Findings and Recommendations

- Correlations used to predict flow friction and heat transfer are not sufficiently specific. The vast majority of correlations currently in use come from constant temperature, constant (atmospheric) pressure, steady flow test rigs. Such tests do not come close to replicating the actual fluid mechanics, and thus the friction and heat transfer coefficients, in an operating engine. Until correlations more accurately represent the multiple phenomena occurring in a regenerator, current codes will only occasionally give the correct results. All current codes rely completely on correlations to give accurate pressure drop and heat transfer results.
- Greater sophistication is necessary in making experimental measurements on regenerators to be used in engine simulations. The complex flows in an operating Stirling engine are very difficult, and perhaps impossible, to simulate in a rig that is itself not an engine. For example, the temperature gradients in an engine have considerable effects on regenerator flows but would be difficult to generate on a rig. Thus, a combination of relatively simple tests with intensive, time-resolved pressure and temperature measurements from actual engines appears to be necessary.
- The cross coordination of explicit and implicit assumptions involved in developing codes and making experimental measurements must be improved. Experiments and computer codes dealing with Stirling engine regenerators are limited in the amount of detailed information they can produce or utilize. Although more specific information is

needed as noted above, the computer analysts cannot ask for information that cannot be measured, and the experimenters should not produce one correlation for each regenerator and flow condition that they test. In addition, averaging assumptions made in making measurements should be the same as those used in applying a correlation in a computer code. Currently, computer codes generally note that oscillating flow data should be used instead of the steady flow information now available. However, these codes do not attempt to mitigate these data limitations, or recognize the limitations of correlations that vary with operating pressure, frequency, or a host of other factors. Thus experimental results are definitely needed.

- Irreversibility analysis could be developed into a useful conceptual tool for designers in dealing with fundamental flow phenomena. Algorithms have been developed that calculate losses in operating regenerators compared with those in an ideal regenerator. These algorithms can calculate losses directly from postulated or measured conditions in the regenerator, rather than requiring extensive analysis to arrive at efficiencies based on such information. These algorithms could thus be a useful tool in dealing with the fundamentals of regenerator performance.

4.5 TRIBOLOGICAL SINKS IN EMERGING INDUSTRIES: ROBOTICS AND ELECTRONICS

Project Staff: J. A. Russell and G. J. Hane

4.5.1 Introduction

This project involved conducting a preliminary review of tribological impact in two emerging U.S. industries: robotics and electronics. These two industries were selected both because they contain significant tribological sinks, and because they are expected to play large roles in the U.S. economy in the future.

The project research identified processes affected by tribology in these industries, and attempted to characterize the nature and magnitude of the associated energy losses and material wear. Productivity losses from material wear

were also considered, since they are of greater a concern to the emerging industries. These initial results could be used to plan research for improving the understanding of tribological processes and to develop improved materials and lubricants to more effectively use energy and materials. Energy consumption figures refer to operational energy for the robotics industry, and manufacturing energy for the electronics industry. The direct and indirect tribological energy losses are summarized, and recommendations for further research are presented.

4.5.2 The Robotics Industry

The notion of using mechanical devices to relieve humans of dangerous or tedious work existed long before the first robot design was patented in the 1950s. However, it was not until the late 1970s that robots began to be used extensively in industrial production in the United States. Since then the use of robots has expanded quickly and industrial robots have become an increasingly common sight in factories around the country.

Common tasks that are performed by industrial robots include spot welding, arc welding, materials handling, surface treatment, and assembly. In 1983, the largest single category of robot was for materials handling (loading and unloading); the second and third largest categories of robots are for spot welding and assembly, respectively. This distribution is expected to change by 1990; materials handling will maintain a similar relative proportion, a significant reduction will occur in the proportion of spot welders, and there will be significant growth in the use of robots for assembly. This is because the market for spot welding robots is expected to reach saturation by the mid-1980s, and assembly applications are expected to grow as sensors and controls are improved. Table 4.4 shows the expected trends in robot applications.

Although the sensors and computer controls for robots are becoming increasingly complex, the mechanical hardware of most robots is largely based on traditional technology. Modern robotic systems usually have three parts: the manipulator, the drives, and the controller. The manipulator is the body of the robot, or its mechanical moving structure. This includes waist, elbow, and wrist joints. The drives activate the joints of the manipulator, and a computer acts as the mind of the robot, serving as the controller and task

TABLE 4.4. U.S. Robot Demand Trends by Application

<u>Application</u>	<u>%, 1983</u>	<u>%, 1990</u>
Materials handling	34	25-35
Spot Welding	24	15-20
Assembly	16	25-40
Arc Welding	11	10-20
Surface Treatment	5	5
All Other	9	7-14

program storer. There is a tradeoff between flexibility and precision of robot motions; in general, the least flexible types of motions will be the most precise.

Most robots are composed of a series of bars connected by joints that allow the rotation and translation of the manipulator. The relative motion of the segments of the manipulator enables the robot to perform its tasks. However, the translation of force and motion from bar to bar creates inefficiencies due to friction and wear. It is at these joints that tribological advances can have a direct impact.

In 1983, the operational energy consumed by all robots was approximately 1.8×10^{12} Btu/year. The largest consumers of total energy, by category, were robots used for materials handling and spot welding. The total operational energy for all robots is expected to rise to 2.9×10^{13} Btu/yr by the year 2000, with the largest consumers being assembly and materials handling.

Major sources of tribological wear in the robotics industry include the chains used to drive the robots, and the bearings, ball screws, and gears used in the shoulder, elbow, and wrist joints of the robot. The lubricants used to reduce wear in these parts are suboptimal for many applications, and frequent maintenance is usually required. The most common cause of robot failure is the wear of parts, and principal wear mechanisms are friction and abrasion.

Direct energy losses due to tribology are caused by losses in mechanical efficiency. Since robots have an overall mechanical efficiency of about 95%,

the maximum amount of direct energy that could be saved from reducing tribological sinks was estimated to be about 5%. Maximum direct tribological energy losses in the robotics industry are summarized in Table 4.5.

Indirect energy losses due to tribology include the embodied energy in the replacements needed for worn chains used in chain drives, bearings used in joints, and hydraulic oil from the fluid reservoir. The indirect energy losses are summarized in Table 4.6.

The robotics community is more concerned with tribological effects on robot productivity than energy losses. The three major productivity concerns are reliability, speed, and precision. Reliability is becoming increasingly important as maintenance requirements or unexpected failures become burdensome. Better lubricants or surface coatings for joints, bearings, and chains would not only improve reliability, but would expand the applications for robot use. Slow operating speeds directly affect robot productivity and profitability; a good way to increase speed without added power consumption is to reduce the mass of the robot. If bearing wear were reduced through improved lubricants the weight of the bearings could be reduced. This would result in a ten-fold effect on the weight of the supporting structure necessary.

TABLE 4.5. Direct Tribological Energy Losses in the Robotics Industry

<u>Year</u>	<u>Total energy consumed, Btu/yr</u>	<u>Direct energy loss, Btu/yr</u>
1983	1.8×10^{12}	3.0×10^{10}
1990	2.3×10^{12}	1.1×10^{11}
2000	2.9×10^{13}	1.5×10^{12}

TABLE 4.6. Embodied Tribological Energy Losses in the Robotics Industry

<u>Component</u>	<u>Embodied Energy Loss, Btu/yr</u>		
	<u>1983</u>	<u>1990</u>	<u>2000</u>
Hydraulic Oil	25.7×10^9	36.4×10^9	76.5×10^9
Replaced Chains	1.8×10^9	2.52×10^9	19.0×10^9
Replaced Bearings	0.85×10^9	1.35×10^9	18.0×10^9
Total	2.8×10^{10}	4.0×10^{10}	1.1×10^{11}

Precision is currently ensured by increasing the bearing stiffness, which in turn increases bearing wear. Therefore, better lubrication at the joints would improve precision as well.

4.5.3 The Electronics Industry

The electronics industry is defined here to include the manufacture of semiconductors, integrated circuits, printed circuit boards, and electronic components such as capacitors, resistors, and transformers. The total manufacturing energy required by the electronics industry was 5.25×10^{13} Btu/year in 1983, with semiconductor manufacture being the largest single energy consuming category. Most of the energy consumed is in the form of electricity; consumption of natural gas runs a distant second.

A long series of processing steps is required to produce the complex products characteristic of the electronics industry. Brief descriptions of these process details will be grouped into general categories for this discussion.

The first processing category is the manufacture of semiconductor grade silicon. Metallurgical grade silicon is powdered and reacted with hydrochloric acid to produce trichlorosilane. The purified trichlorosilane is reduced with hydrogen to ultrapure polycrystalline silicon. Then a single crystal is grown from a bath of melted polycrystalline silicon. This crystal ingot is sliced into very thin wafers with inner-diameter saws, and the wafers are cleaned, lapped, and polished.

The second processing category is the manufacture of integrated circuits on the wafers. The circuit designs are done with computer-aided design tools. Photomasks of the circuit designs are fabricated by electron beam etching onto chromium-coated quartz plates, and the circuit designs are transferred to the wafers by a process called photolithography. The wafers are coated with a photoresist polymer, and light is shown through the mask onto the photoresist. Chemicals are used to cut away the activated photoresist. These patterns are used for the deposition of dopants, other chemical films, or metals. Finally, bonding pads and electrical connectors are installed, and the integrated circuit wafers are cut into chips.

The third processing category is the manufacture of printed circuit boards. Many of the processing steps are similar to those used for integrated circuit manufacture. The board circuits are designed, patterns are generated with photolithography, chips are attached to the boards, and connections are made with conductive metals such as aluminum or gold.

Tribological sinks are found in only a few of the processing steps, since most of the processes do not involve moving parts. The sinks identified occur in slicing, lapping, and polishing wafers cut from silicon ingots, in the blowers and fans used in the clean rooms needed for integrated circuit manufacture, in the vacuum pumps needed for some of the depositions, in the drilling and deburring of holes in the printed circuit boards, in the conveyor belts, and in the contact wear between sliding contacts.

These sinks cause significant dollar and productivity losses, but actual energy losses are quite small. Direct energy losses due to tribology in the electronics industry are estimated to range between $1-2 \times 10^{10}$ Btu/yr. Table 4.7 summarizes these results.

Indirect energy losses due to tribology in the electronics industry result almost entirely from the embodied energy of the blades used for slicing silicon ingots; these blades must be replaced after about 2000 slices. Embodied loss from sliding contact wear, while significant in terms of money and reliability, has an insignificant energy value. Table 4.8 summarizes the results.

TABLE 4.7. Direct Tribological Energy Losses in the Electronics Industry

<u>Operation</u>	<u>Energy losses, Btu/yr</u>
Slicing, lapping, polishing wafers	8×10^8
Blowers, fans for clean rooms	5×10^9
Drilling, deburring holes in PC boards	Negligible
Conveyor belts	$5-10 \times 10^9$
Total	$1-2 \times 10^{10}$

TABLE 4.8. Indirect Tribological Energy Losses in the Electronics Industry

<u>Item</u>	<u>Energy losses, Btu/yr</u>
Slicing blades, for silicon ingots	3×10^9
Contact points	Negligible
Total	3×10^9

4.5.4 Conclusions and Recommendations

Energy losses due to tribological sinks are a relatively small fraction of the energy consumed by the robotics and electronics industries. For the robotics industry, the direct loss is estimated to be about 5% of the total energy consumption; and for the electronics industry, the direct energy loss is estimated to be about 0.02-0.04% of the total energy consumption. If these energy losses were converted to barrels of oil equivalents, the total would be only 7000-9000 barrels per year. Indirect tribological energy losses are even smaller; if converted to barrels of oil equivalents, the total would be about 5300 barrels per year.

However, tribology does cause significant productivity and monetary losses in both industries. Both productivity and special-environment suitability would be improved with the development of better surface coatings and solid lubricants.

4.6 PROJECT FEATURE: RESEARCH APPRAISAL/TECHNOLOGY EVALUATION (RATE)

PROJECT STAFF: D. R. Johnson

Research Appraisal/Technology Evaluation (RATE) is a structured process designed to devise and apply measures of potential research impacts that will be useful in selecting a research portfolio. The process compares the relative potential impacts of projects in terms of technical merit, energy and economic end-use impacts and other national needs and priorities. The primary result is a consistent defensible rationale for project selection. A conceptual framework for the RATE process is shown in Figure 4.2.

ECUT performs generic, cross-cutting research and development. This means that ECUT research provides fundamental data and understanding about chemical

FIGURE 4.2. A Conceptual Framework

and physical properties and phenomena found in technologies that use or convert energy. These technologies, in turn, are embodied in hardware and processes that produce goods and services in the economy. The connections between the generic research and the end-use applications of technologies affected by that research are not always obvious. Often, several technologies and numerous end-use applications are affected, and thus the cross-cutting nature of the research.

A fundamental objective of the RATE process is to identify and trace these connections between fundamental research results and their application in equipment, materials and processes in the end-use sectors. Figure 4.3 shows these linkages and depicts ECUT's role in that progression. In tracing these connections, it becomes apparent that there are several types of benefits to be derived from ECUT research. One type is the development or enhancement of knowledge that will lead to the advancement of the technological state of the art. This can be thought of as a purely technical benefit. Another benefit category includes the energy and economic benefits from using new or improved technologies to produce goods and services in the economy. In an overview sense, RATE is designed to provide data, information and judgments about the degree to which ECUT research projects can yield both technical and energy/economic end-use benefits.

To initiate the process, PNL Systems Analysis Project staff worked with the ECUT headquarters management to develop a value system as a basis for appraising projects. Based on the missions of the ECUT program and the organizations supporting the program, a set of evaluation criteria, weighted according to relative importance, and a set of portfolio guidelines were created. Table 4.9 shows the evaluation criteria grouped according to the major issues they address. Table 4.10 shows the portfolio guidelines.

The evaluation criteria are used to compare projects on a relative basis, resulting in ordinal project rankings for each criterion. These rankings are summed across criteria to arrive at an overall project prioritization. The portfolio guidelines are a crucial part of project selection. They account for

FIGURE 4.3. The ECUT Niche in the R&D Progression

TABLE 4.9. RATE Evaluation Criteria

ENERGY/END USE

Market Size
End-Use Sector Crosscut Factor
Fuel/Feedstock Use or Throughput
Fuel Switching Potential
Multi-Fuel Flexibility
Embodied Energy-Savings Potential

TECHNICAL MERIT

Technical Performance Improvement Potential
Departure from Convention
Novelty in Technical Approach
Degree of Difficulty

ECONOMIC/END USE

Capital Cost Savings Potential
Operating Cost Savings Potential
Productivity Improvement Potential
Reliability Improvement Potential

NATIONAL NEEDS AND PRIORITIES

National Security
International Competitiveness
Strategic Importance

ENVIRONMENTAL IMPACTS

Air Quality
Water Quality
Toxic Waste
Safety

TABLE 4.10. ECUT Portfolio Guidelines

Diversity of Technical Approaches
Major Impacts Potential
Fit into Existing Program (greater depth, less diffusivity)
Mix of Near- and Longer-Term Outputs
Balance of Resource Allocation (critical mass)
Bureaucratic Packagability

factors that are significant in formulating an optimal program mix, given funding constraints and political realities. Thus, the project ranking is a major input to project selection, although it is by no means the sole basis for funding decisions.

Project rankings are based on direct comparisons of projects within each criterion. No strict algorithm or model is employed. This avoids any temptation to rely on a black box to do the thinking, and it avoids the need to "back out" the underlying reasons for the ranking outcome from the assumptions and idiosyncrasies inherent in a quantitative model. It places the responsibility for making judgments with limited information directly on the shoulders of the decision makers.

The basis for these pairwise comparisons is a data base of information, consistent in format and, to the degree possible, in content. Normalized project information for criteria in the technical merit category was generated by the ECUT project field/laboratory managers with the assistance of their staffs. This information was provided in formats provided by the Systems Analysis Project. This information will be provided in a technical appendix entitled "Technical Performance Assessment."

A key criterion in the technical merit category is Technical Performance Improvement Potential (TPIP). Information on this criterion was developed through a workshop involving all ECUT technical project managers. Working sessions were held to identify measures that would describe the physical and chemical parameters operant in technologies being researched in the projects. Where possible, these parameters were to be quantitative measures that were well defined and broadly accepted in the technical community. Examples are "coefficient of friction" for certain tribology projects, "fracture toughness" for certain materials projects and "flame front propagation rates" for combustion projects.

Having defined these measures of technical performance, the ECUT field/laboratory managers arranged them into hierarchies (where possible) and prioritized them in terms of their importance to the performance of a technical operating system. The normalized information provided by the field/laboratory managers focused on describing the difference between the state of the art and

some theoretical or practical maximum limit in a technology in terms of these measures. This difference represents a potential for technical improvement.

Normalized project information for all other criteria was provided by the Systems Analysis Project in an appendix entitled "End-Use Impacts Assessment." This appendix includes quantitative and qualitative information on each project for each of the remaining criteria, which involve end-use impacts.

Quantitative data in the end-use impacts assessment describe the size of the market for research results and the quantity of energy use or throughput potentially impacted by ECUT research. Market size is described in terms of the dollar value of goods whose production could be affected by ECUT research. The basis for these data is the product shipment data in the 1985 U.S. Industrial Outlook published by the U.S. Department of Commerce. Energy use or throughput is described in terms of Btu disaggregated by industry sector, functional use category and fuel type. The basis for this information is the National Energy Accounts data base, developed by Jack Faucett for the Energy Information Administration. This covers 131 economic sectors, (for the purposes of this study), 4 functional use categories (heat and power, transportation, conversion and feedstocks), and 7 fuel types (coal, natural gas, distillate oil, residual oil, LPG, electric and other).

At the time of publication of this report, nearly all the normalized project data is in place. When these data are completely assembled, projects will be compared on a relative basis in pairwise fashion, resulting in an ordinal ranking of projects for each criterion.

After rankings have been accomplished for all criteria, figures of merit will be calculated using a simple summing process with criteria weights as multipliers. A final composite project ranking will be based on this figure of merit. Sensitivity analyses will be performed to determine the effect of variations in criteria weights.

4.7 PROJECT FEATURE: ENHANCING ENERGY CONSERVATION USING BIOPROCESSING, EMPHASIZING THE PRODUCTION OF BULK CHEMICALS

PROJECT STAFF: D. L. Brenchley and G. Strasser (consultant)

4.7.1 Introduction

The Systems Analysis Project contracted with the National Materials Advisory Board of the National Academy of Sciences (NAS) to study the use of bioprocessing to conserve energy. With the supply of petroleum feedstock for petrochemicals certain to dwindle over time, industrial bioprocessing methods for the production of a wide variety of high-volume, low-value chemicals (i.e. bulk or commodity chemicals) using alternative feedstocks such as biomass must be considered. Changing to renewable feedstocks would conserve petroleum and thus contribute to national security through reducing reliance on imported petroleum.

The objectives of the study are to review state-of-the-art biotechnology, and determine the steps necessary to utilize research results to develop applications that could conserve energy through innovative processing and engineering design. The main emphasis is on bioprocessing of bulk chemicals (in contrast to pharmaceutical applications) because it represents a considerably larger opportunity for energy conservation. The technical questions that must be answered are:

- What improvements, if any, can be expected in energy conservation due to the emergence of biotechnology?
- How might these improvements manifest themselves?
- Quantitatively, how significant might these be?
- What course of action should be taken to exploit such opportunities?
- How would such an energy conservation-related use of biotechnological developments fit in with some broader biotechnology policy of the U.S.?

The NAS, under the leadership of Stanley M. Barkin, organized the Committee on Bioprocessing for the Energy-Efficient Production of Chemicals listed in Table 4.11. In addition, he arranged for the participation of a technical

TABLE 4.11. Committee on Bioprocessing for the Energy-Efficient Production of Chemicals

Chairman

GEORGE T. TSAO, Professor, School of Chemical Engineering,
Purdue University, West Lafayette, Indiana

Members

HARVEY W. BLANCH, Professor, Department of Chemical Engineering,
University of California, Berkeley

JEAN E. BRENCHLEY, Director of Biotechnology, Pennsylvania State
University, University Park, Pennsylvania

ARNOLD L. DEMAIN, Professor, Department of Nutrition and Food
Sciences, Massachusetts Institute of Technology, Cambridge
Massachusetts

CHARLES DUNLAP, Section Manager, Engineering Research,
A. E. Staley Manufacturing Co., Decatur, Illinois

ROBERT W. ELTZ, Director, Bioprocess Development, Monsanto
Company, St. Louis, Missouri

WALTER E. GOLDSTEIN, Vice President, R&D Biotechnology Group,
Miles Laboratories, Inc., Elkhart, Indiana

NORMAN N. LI, Director, Separation Research, UOP, Inc.,
Des Plaines, Illinois

ALAN S. MICHAELS, Consultant, Boston, Massachusetts

MARVIN ROOF, Assistant Director of Project Evaluation, R&D
Department, Ethy Corporation, Baton Rouge, Louisiana

WILLIAM A. WEIGAND, Professor, Department of Chemical Engineer-
ing, and Director, Biotechnology Program, Illinois Institute
of Technology, Chicago, Illinois

consultant and several liaison representatives from other organizations and agencies with bioprocessing interests. These participants included Minoo N. Dastoor, ECUT's Biocatalysis Program manager from the Jet Propulsion Laboratory and Gabe Strasser, PNL's special consultant.

James Eberhardt and David Brenchley made presentations to the committee at its initial meeting in December, 1984. These presentations included a description of DOE/ECUT's mission, goals and interests in biotechnology, a summary of PNL's study on Opportunities for Energy Conservation through Biotechnology (PNL-5295) by J. K. Young, E. A. Griffin and J. A. Russell, and a discussion of the following tasks given to the committee.

Task 1--Examine the Opportunities for Energy Conservation with Bioprocessing

The role and importance of energy conservation has been extensively addressed in professional journals, the open literature, and published books. It is generally accepted that energy conservation is in economic competition with actual energy sources as a way of making energy available. Therefore, this task will identify the important near-term and future opportunities for bioprocessing with special emphasis on bulk chemicals production. Pharmaceutical applications are of considerably less interest in this study because they do not seem to represent a significant energy conservation payback. This evaluation would include identifying the expected improvement in this area and, to the extent possible, quantitatively estimating the potential significance of these improvements if implemented. This material will serve to focus the work in the subsequent tasks.

Task 2--Identification of Technical Needs

This task will identify and describe the specific technical requirements needed to implement the opportunities noted in Task 1. The task will emphasize determining whether there are key research and development issues that have not been adequately addressed. For example, scaleup may be a technical issue needing serious attention before bioprocessing can effectively enter the marketplace. In addition to summarizing technical information, these efforts will recommend specific R&D areas and, as appropriate, specific projects.

There are many factors that affect energy conservation. Therefore, some additional topics that may be of interest to the committee include:

- Reduced waste and pollution (in effect, better yields through less byproduct formation)

- Changes in process design to save capital equipment costs and energy
- Milder conditions (total replacement of high-temperature, high-pressure processes by ambient biotechnical routes)
- Use of renewable resources as a feedstock
- More energy-efficient synthesis of specific bulk chemicals
- New bioreactor design
- Increased productivity; for example, by resorting to continuous culture techniques rather than batch processing
- Availability and state of the feedstock (competition with food supply, heterogeneous nature and subdivision of the material, etc.)
- Variability and viability of microorganisms and enzymes
- Problems of separating and purifying from dilute reaction systems.

Task 3--Definition of Implementing Steps

This task will determine the necessary course of action to exploit the opportunities already identified. As the main focus of this task, technical aspects should be viewed with regard to DOE/ECUT's mission. This task should form the basis of an R&D plan.

Task 4--Review of Nontechnical Factors Affecting Implementation

For completeness, this task will identify and describe factors such as industry infrastructure and environmental regulations that may affect the timely implementation of bioprocessing. A variety of non-technical issues, including economic factors, the inadequate interface between bioengineering research and industry, a sparse constituency in the industrial sector, lack of trained technical personnel, etc. could be discussed as a part of this task. This task will also address how the recommendations from Task 3 might fit into a broader biotechnology policy for the United States.

4.7.2 Current Status

The committee met four times during the year and developed a draft report. The draft will undergo internal and peer review and then be submitted

as a final report in April, 1986. The committee's deliberations to date confirm that the advances in molecular biology and genetics and the realization of their potential applications have made the last two decades one of the most exciting eras in the history of science. These advances have provided unique opportunities for development of living systems and biocatalysts (cells and enzymes) capable of synthesizing many organic chemicals of industrial interest from terrestrial or marine renewable resources. Translation of these developments in biological science to large-scale industrial practice is one of the most imposing applied science and engineering challenges of our time.

Opportunities exist in bioprocessing and biocatalysis for the United States to capitalize on its leading position in the new biology to utilize its vast biomass production to conserve energy and nonrenewable carbonaceous materials, including petroleum and natural gas. A key government role is to support generic applied research on such bioprocesses that are presently considered uneconomical by private industry to receive adequate R&D investment.

It is clear that there may only be limited near-term opportunities for providing alternate routes for the production of bulk organic chemicals from renewable resources. Long-term applied research will be required to enable the enormous potential of biological processes to be fully realized. Conventional bulk organic chemicals, and the finished products into which they are now transformed, may not be the optimal end products for large-scale biological production. Research into promising bioprocesses for new families of organic intermediates and new organic products (plastics, textiles) is recommended. While the main focus of bioprocessing is on the production of organic materials, there may be potential impacts on inorganic chemicals as well. Bacterial oxidation of sulfur in solution mining of metals is one example.

A broad spectrum of significant opportunities for energy conservation exists, and many research opportunities in the major aspects of bioprocessing have been identified in this effort. Some examples are listed below:

- Use of renewable resources such as starchy and cellulosic materials to produce chemicals

- Improvement and creation of new biocatalysts (cells and enzymes) by use of molecular genetics, unexploited microorganisms, automated screening and nonphysiological reaction conditions
- Design of novel bioreactors of immobilized enzymes and living cells capable of high productivity and yield
- Improvement of engineering design and scaleup of existing separation techniques and development of innovative separation methods
- Advances in sensing, control and optimization of bioprocesses
- Synthesis of oxychemicals and new families of intermediates and end products with established utility.

5.0 PROJECT STAFF

The ECUT System Analysis Project is managed within the Energy Systems Department at the Pacific Northwest Laboratory. The project manager is David L. Brenchley. David is responsible for the day-to-day conduct of the work, including subcontract management, management of work toward milestones, cost control and quality control. Management oversight at PNL is provided by Jackie L. Braitman and W. Bradford Ashton.

The PNL research staff for the ECUT Systems Analysis Project is shown in Figure 5.1, which also presents the organizational location of task management and task support responsibilities. David Brenchley has primary responsibility for interfacing with the ECUT Division Manager. In addition, Robert A. Hutchinson, Janet A. Russell and Daniel R. Johnson provide key leadership in the thermal sciences, tribology and technical services areas, respectively. Donna C. Debrodt is project editor. The key PNL staff in the System Analysis Project are identified in the following sections. Assignments of staff members to specific project areas are shown in Table 5.1.

FIGURE 5.1. PNL Research Staff for the ECUT System Systems Analysis Project

TABLE 5.1. Project Staff

<u>PNL Staff</u>	<u>Thermal Science</u>	<u>Materials</u>	<u>Tribology</u>	<u>Planning and Evaluation</u>	<u>Research Support Staff</u>
Brad Ashton				X	X
Herb Bomelburg	X				
David Brenchley	X	X	X	X	X
Judy Danko					X
Donna Debrodt					X
Alair Griffin		X			
Gerald Hane			X		
Robert Hutchinson	X		X		
Carl Imhoff			X	X	
Dan Johnson				X	X
Vicki Lee					X
Larry Levine		X		X	X
Steve Lyke	X	X			
Janet Russell		X	X		
Norma June Swannack					X
Tom Thomas			X		
Bettie Jo Westergard				X	X
Carol Winter				X	X
Joan Young		X			

BRAD ASHTON

Brad is manager of the Battelle Washington Office of the Energy Systems Department. He has had extensive involvement with the ECUT program. He is the author of a number of ECUT publications, including The 1981 ECUT Work Element Appraisal.

Brad holds a B.S. in engineering science from the U.S. Air Force Academy, an M.S. in industrial engineering from Ohio State University, and a Ph.D. in industrial systems engineering, also from Ohio State University.

HERB BOMELBURG

Previous to his retirement this year, Herb acted as manager for the oxygen-enriched combustion processes task, and contributed to the pulse combustion task, the laser diagnostics task, and the turbulence and fluid mechanics task. He continues to act as a technical consultant for the Systems Analysis Project.

Herb has extensive experience in fluid mechanics and heat transfer. He has applied this knowledge widely in the space program and in private industry. He also has considerable experience in many other areas, including gas dynamics, LNG safety, combustion and explosion, ballistics, liquid metals, ammonia, wind tunnels, instrumentation, energy storage (flywheels) and gas-cooled reactors.

His educational background includes a B.S. and an M.S. in physics and a Ph.D. in fluid mechanics, all from the University of Göttingen, Germany.

DAVID BRECHLEY

David is the program manager of the Systems Analysis Project and in this capacity oversees all the projects in combustion and thermal sciences, materials, and tribology. He has been a technical contributor on the pulse combustion and materials by design projects. Another significant activity for him is

the National Academy of Sciences study on the usefulness of bioprocessing methods in the production of bulk chemicals.

David has extensive industrial experience. He taught environmental engineering and researched at Purdue University for five years. After this, he was on assignment with the Royal Norwegian Council for Scientific and Industrial Research, where he was a participant in NATO and OECD scientific meetings. His recent experience at PNL includes directing a project for the U.S. Nuclear Regulatory Commission to develop technical bases for regulatory actions on manpower and staffing in commercial nuclear power plants. Prior to this assignment, he managed an oil shale technology assessment project for the U.S. DOE. This involved identifying and quantifying environmental, social and economic problems associated with the development and use of this technology.

His educational background includes: Ph.D. in mechanical engineering from Oregon State University; Master of Divinity from Fuller Theological Seminary; Master's Program in Applied Behavioral Sciences at Whitworth College, and B.S. in mechanical engineering from the University of Washington.

JUDY DANKO

Judy is a technical editor/writer for the Energy Systems Department. Since coming to PNL, she has worked on a variety of publications dealing with energy conservation, nuclear waste disposal, the environment, and health and safety topics.

For ECUT, Judy has edited publications on direct contact heat exchangers and biotechnology. Her most recent effort was the six-volume ECUT Tribology Series.

Judy holds a B.A. in Liberal Arts from Central Washington University.

DONNA DEBRODT

Donna is a technical editor/writer for the Energy Systems Department and is dedicated specifically to the ECUT program. As ECUT editor, she is responsible for overseeing the production of all Systems Analysis documents and products.

Donna has a B.A. in economics and political science from the University of Michigan.

E. ALAIR GRIFFIN

Alair is a research engineer in the Technology Performance Analysis Section of the Energy Systems Department. Alair has been involved in the biocatalysis impact assessment task, and was a primary contributor and co-author of the ECUT report Opportunities for Energy Conservation through Biotechnology. She is now doing research on the impact of the materials by design technology on catalytic processes.

Alair has a strong background in engineering, environment, and computer sciences. Her past experience includes work in industrial conservation, systems analysis, and biological assessment.

She received a B.S. in biology from Jacksonville State University and an M.S. in chemical engineering from the University of Washington.

GERALD HANE

Gerald has contributed substantially to ECUT work over the past five years. His most recent contribution was his assessment of the robotics industry for tribological energy losses.

Gerald received both his B.S. and his M.S. in mechanical engineering from Stanford University, and is currently enrolled at the Kennedy School at Harvard University.

ROBERT HUTCHINSON

Hutch is experienced in analytical and experimental investigations of energy systems and thermofluid phenomena. He has been involved in program planning for the Systems Analysis Project and managed the turbulence and regenerators tasks.

He received a B.E. in mechanical engineering from Vanderbilt and an M.S. in mechanical engineering from Stanford. Hutch also holds a C.P.G.S. in engineering from Cambridge University.

CARL IMHOFF

Carl has specialized in computer simulation of energy and industrial systems, engineering economic analysis, mathematical programming, and decision analysis techniques. Carl has been manager of both the tribology energy sinks task and the tribology research needs assessment.

Carl holds a B.S. in industrial and systems engineering from the University of Arkansas and an M.S. in industrial systems engineering from Purdue.

DAN JOHNSON

Dan's most recent efforts have focused on the Research Assessment/Technical Evaluation (RATE) process begun this year. Dan previously managed and participated in the compilation of the ECUT Energy Data Reference Series and the Executive Information System Report.

Dan received his M.B.A. and an M.E.R. (Master of Energy Resources) from the University of Pittsburgh.

VICKI LEE

Vicki is managing editor for the Energy Systems Department and assisted in the six-volume ECUT Tribology Series. In addition to her ECUT work, Vicki co-authored an information manual for the Institutional Conservation Program.

Vicki received a B.S. in English from Moorhead State University.

LARRY LEVINE

Larry specializes in patent trend analysis as a means of technology forecasting and is utilizing this expertise as Project Manager for the ECUT Benefits Evaluation task. He has also performed studies in competitive technical performance.

Larry holds a B.S. in engineering from the University of Michigan.

STEPHEN E. LYKE

Steve specializes in chemical process evaluation and development research. In this assignment, he supports the Improved Catalysts and Regenerator Analysis tasks.

Steve's past experience has included such projects as conducting laboratory and bench-scale research to develop a molten salt process for conversion of waste HCl gas to elemental chlorine. He also conducted a study of chemicals production from waste carbon monoxide.

Steve received his B.S. in chemical engineering from Northeastern University and an M.S. in chemical engineering from the University of California at Berkeley.

JANET RUSSELL

Janet has considerable experience in projects relating to the conversion of natural products and biomass to energy. As a task leader for the analysis of energy and cost savings from the design of specific catalyst characteristics, she has investigated energy use, feedstock, and cost accounting for industries that use catalysts. She was recently named project manager for the tribology tasks in the Systems Analysis Project.

Her past research has covered such technologies as metal ion catalysis of wood liquefaction, production of levoglucosan from potato starch, production of light oil and asphalt from sewage sludge, and oxidation of asphalt.

Janet holds a B.A. in organic chemistry from Reed College.

NORMA JUNE SWANNACK

Norma June is the administrative clerk in the Energy Systems Department. Her responsibilities involve programmatic financial tracking and control for the project managers and task managers, QA documentation control of project and subcontract files, and general financial documentation for ECUT-related projects.

Norma June has graduated from business college in accounting and IBM key-punch, and taken continuing education classes in business management and computer software applications. She is currently completing a degree in Business Management from Columbia Basin Community College.

M. TOM THOMAS

Tom has recently served as a consultant to the tribology project. Since coming to PNL, he has established the surface science group and an analytical facility.

Tom has worked in the areas of stress corrosion of iron and nickel alloys, corrosion and passivation of amorphous alloys, nonaqueous corrosion of aluminum alloys, and material transfer and chemical changes during wear.

His educational background includes a B.A. in physics from the University of Connecticut; an M.S. in atomic physics, also from the University of Connecticut; and a Ph.D. in solid state physics from Brown University.

ELIZABETH JO WESTERGARD

Bettie Jo has recently joined the ECUT Systems Analysis team and is a contributor to the tribology research task.

Bettie Jo has several years' experience in the pulp and paper industry and has contributed to several technology transfer tasks at PNL.

She has a B.A. in Biology from the University of Omaha.

CAROL WINTER

Carol has specialized in data base development, office automation and computer-based modeling since joining PNL in 1982. She develops computer models and data storage/retrieval systems using high-level programming languages and microcomputer-based software packages. She is currently providing her software expertise as a contributor to the ECUT Benefits Evaluation task. In addition, she has designed and implemented several information systems for Department of Energy program management.

She has a B.A. in Economics, and an A. S. in Journalism.

JOAN YOUNG

Joan has been manager for the biocatalysis impacts assessment task and lead author of the report Opportunities for Energy Conservation Through Biotechnology. Joan has also been a key contributor for the Improved Catalysts task.

She has a strong background in minerals processing technology, cost estimating, uncertainty analysis, computer programming, and environmental analysis. She has experience in alternative energy cost-benefit analysis for such systems as solar receivers, compressed air energy storage, geothermal district heating, and FGD systems for coal-fired plants.

Joan holds a B.S. in chemical engineering from the South Dakota School of Mines and Technology.

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