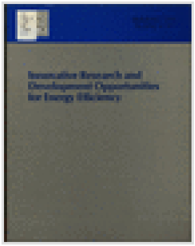

Innovative Research and Development Opportunities for Energy Efficiency (1986)

Pages
130

Size
8.5 x 10

ISBN
0309321247

Committee on Innovative Concepts and Approaches to Energy Conservation; Energy Engineering Board; Commission on Engineering and Technical Systems; National Research Council

INNOVATIVE RESEARCH AND DEVELOPMENT OPPORTUNITIES FOR ENERGY EFFICIENCY

A Report Prepared by the
Committee on Innovative Concepts and Approaches
to Energy Conservation
Energy Engineering Board
Commission on Engineering and Technical Systems
National Research Council (U.S.)

NATIONAL ACADEMY PRESS
Washington, D.C. 1986

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

The National Research Council was established by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and of advising the federal government. The Council operates in accordance with general policies determined by the Academy under the authority of its congressional charter of 1863, which establishes the Academy as a private, nonprofit, self-governing membership corporation. The Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in the conduct of their services to the government, the public, and the scientific and engineering communities. It is administered jointly by both Academies and the Institute of Medicine. The National Academy of Engineering and the Institute of Medicine were established in 1964 and 1970, respectively, under the charter of the National Academy of Sciences.

This is a report of work supported by Contract No. DE-AC01-84CE90142 between the U.S. Department of Energy and the National Academy of Sciences.

Copies available from:

Energy Engineering Board
Commission on Engineering and Technical Systems
National Research Council
2101 Constitution Avenue, NW
Washington, DC 20418

Printed in the United States of America

COMMITTEE ON INNOVATIVE CONCEPTS AND APPROACHES TO ENERGY CONSERVATION

R. STEPHEN BERRY (Chairman), Department of Chemistry, University of Chicago

DAVID BULLEN, Energy Programs, The American Institute of Architects, Washington, D.C.

PAUL P. CRAIG, Department of Applied Sciences, University of California, Davis

RALPH C. D'ARGE, Department of Economics, University of Wyoming, Laramie

LEON R. GLICKSMAN, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge

BERNARD H. KEAR, Exxon Research and Engineering Company, Annandale, New Jersey

J. LAURENCE KULP, National Acid Precipatation Assessment Program, Washington, D.C.

JOEL M. LEATHERS, Dow Chemical Company, U.S.A., Midland, Michigan (retired)

FRED H. POETTMANN, Department of Petroleum Engineering, Colorado School of Mines, Golden

BERNARD I. SPINRAD, Department of Nuclear Engineering, Iowa State University

Expert Advisors

BRIAN FROST, Argonne National Laboratory, Argonne, Illinois

STEPHEN RATTIEN, Department of Technology Development and Transfer, Center for Innovative Technology, Herndon, Virginia

Staff

DENNIS F. MILLER, Executive Director, Engineering Engineering Board

FREDERIC MARCH, Study Director, Committee on Innovative Concepts

ROSENA A. RICKS, Administrative Secretary

ENERGY ENGINEERING BOARD

RICHARD STEIN, The Stein Partnership, New York

THOMAS E. STELSON, Georgia Institute of Technology, Atlanta

LEON M. STOCK, Department of Chemistry, University of Chicago

GRANT P.THOMPSON, The Conservation Foundation, Washington, D.C.

GEORGE S. TOLLEY, Department of Economics, University of Chicago

RICHARD WILSON, Harvard University, Cambridge, Massachusetts

Technical Advisory Panel

HAROLD M. AGNEW, GA Technologies, Inc., Solana Beach, California (retired)

FLOYD L. CULLER, JR., Electric Power Research Institute, Palo Alto California

CHAUNCEY STARR, Electric Power Research Institute, Palo Alto, California

ALBERT R. C. WESTWOOD, Martin Marietta Labs, Martin Marietta Corporation, Baltimore, Maryland

Staff

DENNIS F. MILLER, Executive Director

HELEN D. JOHNSON, Staff Associate

PREFACE

This study was undertaken in response to a request to the National Research Council's Energy Engineering Board by the U.S. Department of Energy (DOE) to examine the role and process of innovation in energy conservation research and development. In particular, DOE desired a report that would identify highly innovative energy research opportunities that could be leveraged with a small budget by the Energy Conversion and Utilization Technologies (ECUT) program, especially with regard to the Innovative Energy Conservation Concepts (IECC) program. The purpose was to provide an up-to-date review of opportunities for and approaches to innovative research as a contribution to the planning processes in ECUT/IECC.

In responding to this request, the Board organized a balanced Committee of experts to conduct the study. Each Committee member is personally involved in some aspect of advanced energy research and drew upon his individual professional experience and access to the research community. (See Appendix A for abbreviated resumes of committee members.)

Specifically, the Committee was given the following tasks:

- Reexamination of the rationale for energy conservation in light of 1985 economic and technological conditions.
- Identification of where major energy savings could be realized by the implementation of new technological tools and solutions;
- Development of a list of technological challenges that, if met, could result in major cost-effective energy gains through conservation.
- Identification of emerging or new technical developments that could be enlisted to create generically new energy systems with greatly enhanced energy conservation potential.

The main emphasis of the study was on Tasks 2 and 3. For a complete statement of task, see Appendix B.

- Description of, but not analysis of, nontechnical incentives to conserve energy.

In pursuing these tasks, the Committee organized a workshop (see Appendix C) that was held December 16-17, 1984, at which experts from several different fields presented papers on frontier areas of research that could contribute to enhanced energy efficiency.

The workshop exposed the Committee to a broad perspective of the energy conservation needs of the industrial, housing, and transportation sectors and to innovative ideas for research related to energy efficiency and use of various technologies. Representatives of these various sectors addressed sectoral requirements for energy efficiency and the opportunities for new methods, technologies, materials, and products that could help solve energy-related problems. Invited researchers in science and engineering disciplines then identified new scientific areas of opportunity whereby research could offer the promise of satisfying the needs articulated by the sector specialists.

These presentations were complemented by a panel discussion among invited scientists and engineers, who helped focus the problems and research issues. On the basis of the findings of the workshop, the Committee established a schedule and plan for the remainder of the study. The main emphasis was on determining how major energy savings could be obtained and identifying emerging technical developments that could lead to new and more efficient energy systems.

Early in the study, the Committee encountered two definitional problems. The first concerned agreement on a working definition of "innovation" and the role of the IECC program in the DOE. Much of the research supported by the ECUT program apparently is already innovative in nature, as is much of the research portfolio of the Office of Conservation. For the Committee, "innovation" is a relativistic term describing the general processes of invention and problem solving. One definition in general use posits innovation as the process through which new or improved producers or processes are taken from initial concept through research and development, engineering, production, and marketing all the way to the marketplace. As such, the term stubbornly resists easy application for the administrative purposes of DOE. Rather than seeking to further define the term "innovation" for ECUT/IECC, the Committee focused on selected applications and on new science and technology research areas offering the promise of significantly enhanced efficiency in the use of energy resources. Thus, the Committee came to agreement on the definition of "innovation" by identifying a selection of opportunities that illustrate the concept.

The second definitional problem related to the concept of energy conservation, or, more broadly, the gain of energy efficiency[1] through use of technology and processes to replace valuable fuels. Here the field of endeavor is simply too large and overwhelming for a limited study that is to have a practical outcome. Because of the extensive nature of the subject, the Committee needed to carefully focus its work. It identified two ways to categorize research opportunities: (1) by examining basic energy-consuming technologies (for example, engine cycles, heat exchangers, materials) and defining the range of user applications and (2) by examining user applications (buildings, industrial processes, and so forth) and defining the range of research to match technology to the application. Both approaches were used in the study, and the Committee limited the range of its activities to areas that appeared to fit well within the ECUT program framework (for example, renewable energy applications have generally not been included). As a result, this report identifies many research problems at the cutting edge of several technologies, without making any claim to being either exhaustive or comprehensive. The Committee believes that vigorous pursuit of the research opportunities identified will contribute to future energy efficiency and have other benefits to the United States.

Although this report was commissioned by the DOE, primarily as input on its ECUT/IECC program area, it is not intended to be a justification of the programs. The Committee has gone beyond merely recommending research areas and offers guidance for research management strategies, with the expectation that ECUT/IECC will find it useful.

Finally, although this report is addressed to the study sponsor, the Committee hopes that it will be read by energy policymakers, individuals in private sector research organizations and university laboratories, and individual inventors who seek new opportunities.

---

[1]In preparing this report, the Committee chose to use the term "energy efficiency" rather than "energy conservation" in the title as well as in the text." The Committee believes the term "energy efficiency" better expresses the spirit of the research and development programs that are recommended.

The Committee would like to thank Dennis Miller, Executive Director of the Energy Engineering Board, for organizing and managing this effort; and Frederic March, Study Director, who worked with the Committee in preparing the report. The Committee also thanks Rosena Ricks, Cheryl Woodward, and Helen Johnson for their roles in organizing the workshop and other meetings and in preparing this report.

R. Stephen Berry, Chairman
Committee on Innovative Concepts
and Approaches to Energy Conservation

1

INTRODUCTION

This report is about research opportunities to develop new technologies that will make more efficient use of fuels in the industrial, power, transport, and building sectors. The context for the detailed description of technical research opportunities presented in Chapter 2 is given in this introduction.

The starting point is the rationale for future energy efficiency from the perspective of current 1985 world energy economic conditions. Two strategies are outlined: (1) purchasing insurance against future contingencies and (2) ensuring continued progress in making energy consumption more economically efficient.

Although this report deals primarily with the technical (that is, applied technology) means for achieving improved energy efficiency, it is important to see these within the context of the nontechnical approaches available to public policymakers. Such a view is provided by a description of how the nontechnical approaches are actually quite dependent on technical solutions. Since this report promotes innovation as a specific strategy for new achievements in energy technology, the introduction concludes with a brief discussion of innovation as a public policy issue.

Chapter 2 contains the major thrust of the report, discussion of the many areas of technical research opportunities that exist. It is seen that many scientific and engineering problems can be solved by research and development (R&D) approaches to the goals of improved energy efficiency.

Chapter 3 focuses on the research management strategies available to Energy Conversion and Utilization Technologies and Innovative Energy Conservation Concepts programs for screening and selecting projects to fund and promote from the universe of opportunities. Some of these strategies call for specific, but not necessarily large, investments by the agency.

Chapter 4 examines the implications of the Committee's work and summarizes its recommendations.

THE RATIONALE FOR ENERGY EFFICIENCY: A 1985 PERSPECTIVE

In 1973 the main stimulus for federal support for research on the development of more efficient energy technologies was the fuel scarcity induced by the oil embargo, and the corresponding rapid price increase, imposed by the Organization of Petroleum Exporting Countries (OPEC). As part of a strategy to become energy self-sufficient, the United States attempted to alleviate the adverse impacts associated with the immediate and expected longer-term oil scarcity (Federal Energy Administration, 1974). The many resulting efforts of the United States to reduce fuel consumption, inappropriately labeled "energy conservation," were received by the public in various ways. Early attempts at conservation, on one hand, were disparaged by energy-producing communities, who believed that the elasticity of fuel demand and/or supply was extremely low. On the other hand, radical life-style changes to conserve energy were advocated by diverse constituencies who believed that austerity was the appropriate response to perceived energy problems.

Meanwhile, the problem of excessive energy costs was being quietly and effectively pursued by engineering practitioners in the energy-intensive industries, who were looking for economic technical means to increase the energy efficiency of their operations. Thus, the total productivity factor (optimization of energy, capital, labor, and material) became paramount in addressing U.S. and world markets.

As a result, energy demand in every sector has changed drastically over the 12 years since 1973 (Darmstadter et al., 1983; Marlay, 1984). Initially, some short-term "housekeeping" improvements were made, such as turning off unneeded lights, not heating unused rooms, and fixing leaky steam pipes. Then there began a succession of changes from old equipment and processes to new and more energy-efficient means to achieve the same ends, such as more fuel-efficient automobiles, houses, and industrial fixtures. The net result of the changes has been a significant reduction in the growth of the demand for energy, thereby creating a market for new efficient technologies.

The nation continues to remain vulnerable to price fluctuation and the disruption of imported energy, with the Middle East still an important (if decreasing) consideration in long-term energy planning. Given the experience and accomplishments gained in the past 12 years, the question is raised: Is continued federal participation in R&D directed toward energy efficiency justified? If the answer is yes, the criteria for selecting the areas of R&D and for setting the appropriate level of federal funding should be specified.

In the near future (the next 3 years), barring unpredictable crises, energy in useful forms is expected to remain at reasonable prices. For example, the average cost of electricity at a power station will probably hover around 7¢/kWh in real terms or will slowly rise, even as the mix of electricity-generating technologies changes. For the next 5 to 15 years, a modestly optimistic view assumes that improvements in coal combustion and pollutant removal, coal gasification, photovoltaics, advanced light water reactors, and ethanol and methanol engines, as well as other energy technology developments, will help maintain the stability of electric and other energy costs even as the price of basic imported or domestic fuels fluctuates. Thus energy availability and relative cost will depend on energy technology R&D's keeping pace with the changing availability of the nation's and the world's energy resources. This is the context in which energy efficiency R&D must be evaluated.

There are two motivations, and corresponding strategies, for a federal role:

- Insurance--providing a feasible set of technological options that can be called upon in response to gradual or sudden fuel scarcities or unforeseen crises.
- Efficiency--enhancing economic productivity by increasing the efficiency with which energy is used on a continuing basis.

These issues are explored in the following sections.

The Insurance Strategy

The insurance strategy represents technological contingency planning. With a knowledge of technological feasibility, costs, and procedures for implementation of an option, it is possible to maintain technologies in reserve that may not be economically viable under present market circumstances. Sometimes called "mothball technologies," they have a rationale similar to that for the strategic petroleum reserve. Their costs are called insurance, and the upper limit on how much should be spent on R&D can be determined in principle by using the standard criterion of present value; that is, the marginal costs of development and deployment should be no greater than the present value of the marginal costs of coping with a scarcity crisis, multiplied by the probability of that scarcity. The terms in this equation are easy to express in words but are virtually impossible to quantify. They must be left to the intuitive judgment of the experienced professionals: the probable costs of R&D, to the research managers; the cost of coping in an emergency, to students of events like the 1973 oil crisis and to those familiar with costs of emergency regulation; and the probability of a scarcity crisis (the most difficult of all), to either oracles or those who would estimate it as part of a political policy. However difficult these quantities may be to estimate, it is helpful to analyze the problem by its components, each of which can be addressed by appropriate expertise.

An important consideration, the time required for the R&D and for the deployment of a technology, must be introduced in this examination of the insurance strategy: the more extensive the technological change, the longer the lead time for R&D and implementation. An evaluation of the costs, however approximate, should not treat the introduction of a new technology as if it were instantaneous. The costs must be computed in terms of a phaseout of the old technology and an introduction of its replacement at a rate consistent with the time needed to construct the new technology and to operate it reliably (that is, the "learning time"). Holding a technology in reserve does not mean not using it. To the contrary, it means the strategic deployment of pilot and prototype installations to ensure that operational experience remains current and to provide the ability to rapidly expand installations.

The development of currently unprofitable technologies to be held in reserve for emergencies is obviously not a task that private firms will carry out on their own initiative. It is entirely a matter of public benefit; whether it is done is a matter of public policy. Specifically, public policy questions enter into estimation of the costs of responding to scarcity crises in the absence of alternative technologies and the estimation of the likelihood of such crises. It is obviously not within the charge or the capability of this Committee to make such estimates, but the Committee does explicitly indicate how the Department of Energy (DOE) can address the evaluation and selection of R&D projects for energy efficiency (see in Chapter 3 the section Criteria for Project Selection, which includes the estimates of costs, benefits, and probabilities that should enter into the decision of which R&D projects to support).

Hence, in the insurance context, it is important for DOE program managers to contemplate a range of options. They can then evaluate proposed projects not only in terms of their R&D costs but also in terms of cost and time for implementation, the extent to which they can substitute for present alternatives if necessary, and the costs, if any, of keeping them in mothballs until required.

An illustration of the insurance strategy can be drawn from the context of electricity supply. Assume that scientific evidence that the greenhouse effect poses a dangerous threat becomes convincing to policymakers during the next 5 years, making urgent the rapid replacement of fossil fuel combustion with other forms of primary energy. The technologies that currently appear to have the required large-scale sustainable potential, in order of increasing uncertainty, are fission, breeder, and fission/fusion reactors, photovoltaics with storage, and fusion reactors. These can be considered part of a basket of insurance options that may include contributions from other technologies. The time required to bring these to commercial practicality depends on the level of commitment and the uncertainties of the R&D process. Speculating, such time may be no sooner than 10 years for breeder reactors and 20 or more years for fusion at current levels of support--shorter times if R&D commitments are increased. An additional several years for planning, design, and construction would be needed for any of these options to significantly affect the mix of electricity supply technologies. The cost of the research to bring any of them to the development stage and to commercialization can be estimated, with appropriate statements of probability. If the annual costs of the untoward consequences of the greenhouse effect can be correspondingly estimated, even roughly, the insurance strategy of buying R&D now can be assessed in economic terms. Other future events such as acid rain or various fossil fuel price scenarios can be similarly analyzed in terms of insurance.

The Strategy of Efficiency

Economic efficiency in relation to energy as an input can be improved when:

1. The consumption of energy is reduced in producing a given product or service, thereby lowering the cost;
2. An additional input of energy displaces other inputs (labor or materials), thereby lowering the cost (for example, electric-driven automation reduces labor and conserves materials);
3. An additional input of energy adds value by improving an existing product or service or enabling the creation of new products and services, in which case the willingness to pay for the added value is the measure of economic utility (for example) air conditioning adds comfort, which has value);
4. A new product or material is produced, the use of which reduces energy consumption in an economic manner for some operation or function.

Economic efficiency is pursued by policymakers as a means to improve living standards. Part of this goal involves improving the competitiveness of U.S. products for export.

In planning R&D for energy efficiency, federal thinking has been dominated by the narrow goal of reducing unit energy consumption rather than by the broader goal of economic efficiency. Some of the research topics suggested in Chapter 2 involve the development of new materials that actually require more energy to produce than what they replace; however, the new materials produce added value by decreasing the operational and repair costs of machinery, including the reduction of energy consumed in operations.

The private sector is motivated by economic efficiency at the level of the firm. It will invest in energy R&D when certain conditions are met: the expected return exceeds that of alternative investments, the benefits can be captured, the payback period is not too long, and the scale of investment does not overly expose the firm to risk. These are, of course, subjective evaluations that vary from firm to firm.

A number of public economic and social goods often cannot be captured by the private investor: insurance against future fuel scarcity, national defense, and environmental protection.

Taking the above observations into account, the policymaker justifies a federal investment into energy R&D that increases economic efficiency when the private sector fails to invest by virtue of (1) uncapturable benefits; (2) microeconomic factors such as risk to the firm, payback period, return on investment, scale of investment, and competing investments; and (3) economic distortion introduced by regulatory processes. In today's industrial and financial climate, the private sector's bias is toward short-term, quick-payback, minimum risk projects requiring low capital investment. Such projects tend to produce only minor incremental improvements to existing technologies rather than new and innovative technologies. When the result is a failure to produce innovation that is economic to the nation, the government must choose between policies that stimulate the private sector to invest in R&D and those that make the government a major investor.

Since there is almost always a gap between national technology development needs and the private sector's ability or willingness to respond, there is a continuous need for a federal R&D effort. The following review of the rationale for energy efficiency provides a context for the innovative R&D opportunites for energy efficiency introduced in Chapter 2.

NONTECHNICAL INCENTIVES FOR ENERGY EFFICIENCY

These incentives relate to actions that do not involve the substitution of more efficient technology for energy consumption. Although this report focuses on technical incentives that motivate the search for and application of technological solutions, policy options are available to the federal government that do not depend directly on the technologies. However, the effect of most of these incentive policies, although not directly technical, nevertheless is to stimulate the market for more energy-efficient technologies.

The literature on such nontechnical incentives is vast, dating back to the first Arab oil embargo and the publication of a Federal Energy Administration report (1974). There is also the assortment of various state energy emergency contingency plans, in which sudden curtailments of the availability of imported oil are anticipated. A detailed treatment of nontechnical incentives is contained in a DOE-sponsored report by Battelle Pacific Northwest Laboratories (1980). The Committee did not study these nontechnical policy options in detail but discussed them as possible alternatives to the strategy of developing new energy-efficient technologies.

Before proceeding to indicate the range of these nontechnical options, whatever their merits, it should be said that they are in no way to be a considered a substitute for advanced scientific research. As public policy instruments, they have their appropriate time and place. In most cases, the efficacy of these nontechnical options actually depends on future technical developments in energy efficiency. The subject of nontechnical incentives is actually part of the larger subject of technology transfer, as reviewed in a recent DOE publication (Department of Energy, 1984b.)

Taxes

Taxes are a major instrument of public policy whose basic revenue-raising rationale has been overlayed by motives designed to promote socially desirable behavior. In the energy area, this takes the form of taxes on the fuel commodities themselves, the technologies that consume fuel, and on nonfuel technologies such as solar energy. To the extent that such taxes are not too large and are proportional to those taxes on all other goods and services that have the intent to raise revenue only, they do not modify energy consumption behavior. As occurs with any commodity, as taxes on fuel are increased the price to the consumer increases and demand falls. Consumers seek to satisfy demand by substituting cheaper fuels or technologies, which further reduces their demand for fuel. Incentives to use such technologies in the form of rebates, accelerated depreciation allowances, and so forth tend to sharpen the economic choice for fuel consumers. If no affordable fuel or technology substitute is available, consumers are forced to increase their tolerance for discomfort and inconvenience and to modify their life-style. Ultimately this can lead to genuine hardship and deprivation, unless tax-offsetting subsidies like lifeline electric utility rates are employed. Thus one of the rationales for an energy R&D program is to create future technology options for responding to nontechnical tax policies that alter the way the consumer makes an economic choice.

Promulgation of Standards

Simply stated, standards impose a required norm on the rate of energy expended per unit of operation of some kind of machinery or structure. The standard can apply to individual machines such as cars, air conditioners, and household appliances, to a house or building, or to the statistical properties of a product line, as in the case of an average gasoline consumption standard for the entire fleet produced by a manufacturer.

The availability of technical options is important to the success of the nontechnical policy. Not only must the more efficient technological options be available, they must also be affordable. The alternative, as in the case of taxes, is the imposition of discomfort, inconvenience, or worse on the consumer. A major rationale for energy efficiency standards is to motivate the private sector to invest in the R&D that will produce cheaper products that meet or exceed the standards.

Imposition of User Restrictions

Rationing of fuel commodities, imposition of blackouts or brownouts, prohibition of prescribed uses of energy, and other such measures are associated with public emergencies induced by war or embargo. They are not considered among the routine options for economic planners projecting changes in the supply-demand relationships of energy commodities. Nevertheless, they are important instruments of public policy in emergency situations and have been used from time to time. Orderly planning for such contingencies is the subject of the various state energy emergency contingency plans.

The availability of future technology is an important factor in minimizing the need for such extreme nontechnical measures and minimizing their adverse effects if they are indeed applied.

Changes in Life-style

In addition to the mechanisms discussed above, there are policy options that can alter life-styles to reduce national consumption of energy. These are somewhat speculative and probably controversial but are nevertheless part of the public debate. They include the promotion of dispersed smaller-scale electric energy sources, recycling of energy-intensive throwaway items, elimination of petroleum-based fertilizers and insecticides in agriculture, wider use of public transportation systems in urban areas, and energy-efficient zoning.

Energy efficiency R&D will contribute new technologies that may make some of these nontechnical incentives feasible in the future. In fact, it should be clear that if the nontechnical incentives are to be included as public policy instruments, their successful deployment will very much depend on the availability of new technical options, many of which have yet to be conceived. Exploring a range of such options is the major thrust of this report.

Additional Nontechnical Incentives

The following additional nontechnical incentives are mentioned only to acknowledge their role in a comprehensive policy of energy efficiency: education, training, data banks, information dissemination, marketing, advertising, cost sharing, demonstrations, licensing, franchising, patents. All of these presume some underlying positive technological development.

INNOVATION AS PUBLIC POLICY

The literature on innovation as a focus of public science and technology policy is so vast that it can be only briefly mentioned. The subject is not new. The Kennedy administration mobilized a White House Panel on Civilian Technology in 1961 (Michaelis, 1984). Suffice it to say that innovation appears to be a permanent fixture of the annual legislative process and an important rationale for the allocation of research funds to DOE conservation programs (Crane and Hack, 1984; Marcus, 1985; Schacht, 1985).

There is also a classic literature on innovation as a cultural-historical process which can provide excellent general insights (Burke, 1979; Morison, 1966).

Although this report is concerned with innovation for the purpose of increasing energy efficiency, innovation as a fixture of public policy has a broader purpose: to maintain and enhance U.S. leadership in a whole spectrum of technical areas--military, industrial, and agricultural. Energy efficiency is simply one of many technological areas, such as communications and transportation, in which the development of advanced technology contributes to a number of public goals (Georgia Technology Institute, 1974; Harmon, 1980; Holden, 1980; Lundstedt et al., 1982).

Finally, the term "technology transfer," which is the process by which innovative technology is made to enter the marketplace, is briefly mentioned. The federal role in promoting technology transfer is very closely tied to its role in innovation (Department of Energy, 1984b). The subject is vast and the treatment can be quite technical (Brown, 1981; Mansfield et al., 1982; Walcoff et al., 1983).

Even though the Committee did not extensively dwell on the general interrelated subjects of innovation and technology transfer, the Committee's own work represents a contribution. Because the major focus of the study was the specific technological innovations that are possible for achieving energy efficiency, the process of stimulating innovation and transferring it to the marketplace is treated in far less detail than are the technological opportunities themselves.

2

AREAS OF RESEARCH OPPORTUNITY

Presented in this chapter is a review of opportunities that exist for conducting research that will contribute to current technology, materials, and information and thereby result in the more efficient use of energy resources.

The Committee did not use a prescribed methodology in conducting the review, such as that conducted on behalf of the Energy Conversion and Utilization Technologies (ECUT) program (Battelle Pacific Northwest Laboratories, 1981), nor did it undertake a comprehensive review of the research literature (see Battelle Northwest Laboraories, 1982). Rather, a contemporary technology outlook is presented that reflects the individual viewpoints of the Committee members, most of whom are currently involved in some aspect of energy conservation research; it is augmented by the discussions held at the workshop on December 17-18, 1984 (see Appendixes A and C).

The Committee does not attempt to prescribe future energy conservation research by the Department of Energy (DOE) or to review past efforts under the ECUT and related programs, as did Oak Ridge National Laboratories in reviewing the Energy-Related Inventions Program (Soderstrom and Rorke, in press) and the Appropriate Technology Small Grants Program (Cardinal Management Association, 1984). The Committee does, however, indicate a range of innovation opportunities and identifies selected examples related to recent developments in advanced technology that should help inform and assist the ECUT planning processes. Some of these examples may have already been part of ECUT or other Office of Energy Conservation programs, some may have been considered previously but not pursued; and, more important, some are totally new opportunities for energy efficiency R&D.

Major technical areas are described in which new, energy-efficient technologies seem achievable and in which additional support could have high leverage in hastening the progress of specific new approaches. The Committee selected these technical areas on the bases of extensive briefings and discussions, as well as on topics raised at a wide-ranging workshop (see Appendix C) intended to explore a variety of technical areas as they are currently viewed by their practitioners. These areas are:

- Heat transfer
- Heat engines and engine cycles
- Sensors and automatic controls
- Materials processing
- Special materials
- Building envelopes
- Intelligent buildings and advanced design tools

Certain important technologies for energy efficiency, requiring further R&D, are likely to be pursued but were not included in this review. By this we mean the collection of renewable energy technology systems falling outside the scope of the ECUT program. Similarly, energy storage and the spectrum of applied research opportunities applicable to the electric utility industry for improved generation, transmission, and distribution of energy were not included because DOE has well-developed R&D program offices covering these areas, and the Committee wanted to limit its scope.

Finally, since no committee or project team could expect to be comprehensive about opportunities for innovation in energy efficiency research even within selected areas, there are no doubt many meritorious ideas and approaches that did not occur to the Committee. Therefore, this review is simply a tool for approaching the subject; ideally, it will to help ECUT find and support additional areas of innovation. In Chapter 3, ways in which ECUT/IECC can continue the process of identifying innovative R&D topics for energy efficiency are discussed.

HEAT TRANSFER

Heat transfer is a basic mechanism common to the functioning of buildings, industrial processes, and engines. A range of potential research areas are discussed in this section under the following headings:

- Equipment needs
- Working fluids
- Resistant materials and insulation
- Component replacement

Some of the research directions indicated in the discussions are somewhat general because they are examined in more detail under subsequent topics. For example, resistant materials are discussed further in the Special Materials and Building Envelopes sections.

Equipment Needs

Recommendations:

- o Conduct research on some of the detailed mechanisms for heat transfer, such as heat transfer in turbulent flows, innovative heat exchanger designs, and materials mass transfer through porous materials; also on radiation heat transfer involving gray fluids in complex geometries.
- o Develop improved heat exchangers (application to kraft pulp mills have one quad potential).
- o Explore applications of electrochemical high temperature heat to electric conversion devices.

Discussion:

Heat transfer has many aspects that have not been completely explored, such as the detailed mechanisms for nucleation and film boiling, radiative heat transfer involving gray fluids in complex geometries, and behavior in turbulent and multiphase flows. These and similar problems are the subjects of significant ongoing research aimed at developing new models and explanations for phenomena for which existing models are inadequate for design tasks requiring increasingly accurate prediction of results.

Heat transfer equipment, its performance and costs, are limiting factors in a host of system concepts. For example, the Stirling engine, originally invented as a demonstration of the validity of the ideal Carnot cycle, remains by and large impractical because the heat transfer surface demanded for its efficient functioning is too heavy and expensive to be economically usable. In the Rankine cycle, used for many types of electric power generation, the efficiency falls short of that in the Carnot cycle in part because multiple reheat cycles require costly heat exchangers to recover the energy of lower-pressure steam. If heat exchanger costs were reduced, more feedwater heaters using rejected moisture would be used.

Related energy extraction concepts dependent on heat transfer, such as Ocean Thermal Electric Conversion systems and bottoming cycles in conventional power plants, also are circumscribed by high heat exchanger costs. Quite novel ideas such as the use of a two-temperature electrochemical battery system to convert high-temperature heat to electricity (charge at high temperature, discharge at low temperature) are defeated by heat transfer equipment costs.

Steam generators and reheaters, among the bulkiest and most expensive components of nuclear power plants, are the source of a large fraction of system downtime and maintenance expense. New equipment concepts and materials are needed. An important opportunity for new heat exchanger equipment to capture a large amount of currently wasted energy lies in the kraft pulp mill. There are about 200 kraft mill complexes or their equivalent in the world today. The typical capacity is 1,000 tons/day of pulp. Kraft pulp mills and the associated paper machines in a modern integrated fiber-mill complex have huge energy flows in water and gaseous effluent with low thermodynamic availabilities. Existing technology has not made it economically feasible to develop this opportunity, largely because of the difficulties of heat transfer across small gradients. New innovative equipment concepts are required, which, if successful, could perhaps contribute a quad to the national energy budget.

Radical and innovative changes in special-purpose industrial furnace design to provide for more rapid and precise heating of parts are of interest. A wide range of new heating technologies can be explored, including microwave, ultraviolet, infrared, laser, plasma, and induction heating.

Working Fluids

Recommendation:

- Search for fluids that will not attack surfaces at high operating temperatures.

Discussion:

Although a few heat exchange fluids, such as pure liquid sodium (which of course poses a hazard) and helium, do not seem to attack standard heat exchanger materials, virtually all other known working fluids do. In fact, the two most common working fluids, steam and carbon dioxide, are both persistent oxidizing materials at high temperatures. In spite of the most exacting manufacturing standards, evidence to date is that no heat exchange surface can be operated in contact with these fluids at high temperature without concern for failure. Not all the mechanisms of corrosion are well understood yet, but the oxidizing nature of the working fluids is at least a trigger for the effects that have been experienced. A better understanding of the corrosion mechanisms will contribute to the development of improved working fluids.

Resistant Materials and Insulation

Recommendations:

- Coat materials with oxide films to resist oxidative attack.
- Solve the problems of ceramic heat exchangers.

- Develop improved methods for joining nonductile materials.
- Improve the understanding of how soil acts as an insulation and heat storage medium and how it is influenced by moisture migration.
- See recommendations in Special Materials section.

Discussion:

Basic chemistry suggests some new and potentially radical approaches to improve the resistance of equipment and component parts to chemical and physical attack. One approach is to use substances that can resist oxidative attack, such as materials that are already oxides, and one direction to take is to seek good manufacturing techniques for coating all vulnerable surfaces with an oxide film that is both rugged and not too great a thermal barrier to heat transfer. Beyond surface treatment, the ultimate in this direction is to build all-ceramic heat exchangers.

A major problem with ceramics is that they tend to be brittle and to be heat insulators. Nevertheless, some heat-conductive and tough ceramics do exist and thus this line of development deserves to be encouraged. There should be a parallel effort on the joining of nonductile materials, probably using cements that are themselves nondegradable--another challenging concept to develop.

The problem of insulation becomes more demanding whenever smaller components are used in industrial systems. As the surface-to-volume ratio becomes larger, previously tolerable heat losses become intolerable, and the result is energy loss and equipment damage.

The health hazards of asbestos have virtually eliminated the routine use of this otherwise very valuable material, and a less risky and equally inexpensive material of equivalent insulating capability has not yet been found. The development of insulating materials made out of safe, common substances is needed just as much for industrial settings as for buildings. There are some higher-technology approaches, such as the development of coatings with unusually high thermal resistivity, perhaps incorporating vacuum sublayers to furnish at least the first barrier against undue heat loss.

For retrofit insulation of the exterior walls of existing buildings, there is a critical need for thin insulating material with high thermal resistance that does not create a fire hazard, does not lose its insulating value with age, and is resistant to moisture transfer. The use of low-conductivity gases or evacuated microspaces within the insulation should decrease its effective conductivity. Such an insulation could also be used to improve the performance of appliances.

The use of soil as an insulation and heat storage medium around building foundations and earth-sheltered structures requires an understanding of soil conductivity as influenced by moisture migration. An understanding of the mass transfer of liquids through porous materials is also important in anticipating possible problems of moisture accumulation in insulated wall cavities. A better understanding of moisture percolation will contribute to the use of soil and other cheap materials that are subject to water infiltration or percolation.

Component Replacement

Recommendation:

- Develop cheap materials that degrade gracefully in heat exchangers.

Discussion:

Instead of expensive armoring of components in certain environments, one line of attack is to use heat exchange components that are sufficiently inexpensive that design for limited life and replacement is economically feasible. The standard automobile radiator is a possible paradigm. Of course, the standards for industrial systems are a good deal more stringent than for a car radiator, even for a heat exchanger of limited service life. When component failure occurs, it must be graceful; that is, it must result merely in degradation of function rather than destruction of the equipment. Many systems that incorporate heat exchangers (nuclear power plants are an extreme example) are not presently designed for routine replacement of components but can be redesigned for that capability. A presently unpopular approach, namely, the use of a system with a great many manifolded heat exchanger units rather than a few loop systems, could present the best opportunity for both minimizing field construction (always expensive in the erection of large systems) and facilitating graceful system degradation and component replacement.

HEAT ENGINES AND CYCLES

Heat engines and cycles include all internal combustion engines, steam engines; and systems that operate on working fluids, such as compressors for air conditioning, refrigeration, and other applications.

This section describes research approaches in the following areas:

- Augmentation of heat transfer
- Reduction of heat transfer
- Reduction of thermal distortions and friction
- Improvement of combustion characteristics
- Improvement of path of piston
- Improvement of control within cycle
- Improvement of materials to resist higher temperatures

Augmentation of Heat Transfer

Recommendations:

- Improve heat exchange within the regenerator of Stirling and Ericsson engines.
- Augment air-side heat transfer in air conditioners and compressors by exploring new surface geometries, lower fluid velocities, and use of new materials.
- Augment gas-side heat transfer in high-temperature heat exchangers of bottoming cycles by using shallow fluidized beds.
- Improve cooling techniques for turbine air foils and use ceramic materials to achieve higher power densities.
- Develop lightweight heat exchangers for bottoming cycles used with diesel or gas turbine engines.

Discussion:

Augmentation of heat transfer can achieve substantial improvements in the efficiency of heat engines, refrigeration cycles, and heating and ventilating equipment. In air conditioners and heat pumps, the irreversibilities in the heat exchangers cause efficiency losses of the same magnitude as the irreversibilities in the refrigerant compressor-motor drive. The heat exchanger losses are caused by the relatively poor heat transfer on the air side, which requires operation with substantial temperature differences to maintain adequate heat flow. Improving air-side heat exchange would improve the efficiencies of such devices. For bottoming cycles used with diesel or gas turbine engines, high-temperature heat exchangers are needed that are lightweight and resistant to fouling and thermal stresses.

If the heat exchange in their regenerators could be made more efficient and the fluid friction reduced, it would be possible to improve the performance of Stirling and Ericsson engines. These coupled problems, along with poor part-load performance, have always been among the biggest stumbling blocks to making either of these theoretically efficient cycles into economically practical devices.

Air-side efficiency in air conditioners and compressors can be increased by improved methods to augment the air-side heat transfer; possible approaches include new surface geometries that give higher heat transfer at low (laminar) velocities. Thus, less expensive, more reliable techniques for fabrication of large air-side surface areas are needed. This might be accomplished by the use of new materials such as high-conductivity polymeric materials and new fabrication methods.

New ceramic or composite materials could be useful in high-temperature heat exchangers. Augmenting gas-side heat transfer in bottoming cycles with very shallow fluidized beds may be applicable for high-temperature dirty streams such as exhaust gases. Low-density fluidized beds may also improve air-side heat transfer in low-temperature exchanges.

Adoption of high-efficiency cooling techniques for turbine airfoils used in transportation and new ceramic materials for the turbines themselves will allow higher power densities and consequently greater cycle efficiencies in gas turbine engines.

Reduction of Heat Transfer

Recommendations:

- Seek to reduce turbulence and to approach laminar flow within the cylinder.
- Pursue additional research on the fluid dynamics within the cylinder to extract more work from the heat produced.

Discussion:

Improvements can be made in the degree to which a real engine's stroke actually approaches adiabatic operation by minimizing heat transfer across the boundary layer between the working fluid and the chamber walls. This means making the working fluid's motion more nearly laminar and less turbulent at the smallest possible scale. This must be balanced by the turbulence necessary for good mixing and combustion of the fuel and air. In a diesel engine, reduction of heat transfer losses and the use of turbo compounding can lead to a 15 percent increase in the cycle efficiency. Reduction of the heat transfer requires attention to both the fluid dynamics of the working fluid and the use of resistant materials, such as new ceramic compounds, on the surface of the chamber.

The major inefficiencies in modern internal combustion engines, whether Otto, diesel, or combined cycles, arise from heat losses in the hottest part of the cycles. The more work that can be extracted from heat at its highest temperature, the more efficient is the engine. Here is a general problem seeking a solution. One possibility is described below (see Improvement of Path of Piston section), but other approaches may be used, such as capturing the work that is potentially available while the gas in the engine is at its peak temperature, before heat is lost through the walls and temperature declines. Such an improvement would make the internal combustion engine perform more nearly like the ideal Carnot engine.

Reduction of Thermal Distortions and Friction

Recommendations:

- Study convective heat transfer in reciprocating engine cylinders.
- Study the relationships among flame propagation, fluid dynamics, convective heat transfer, and solid conduction.

Discussion:

Convective heat transfer in reciprocating engine cylinders is characterized by turbulent, transient flow. Heat transfer under such complex flow conditions leads to nonuniformities that reduce engine performance. This phenomenon must be better understood to enable more efficient, more nearly adiabatic processes to be designed, as previously described. Temperature nonuniformities within an engine piston and cylinder cause thermal distortions that increase sliding friction. A solution to this problem requires an understanding of the relationships among flame propagation, fluid dynamics, convective heat transfer, and transient solid conduction.

Improvement of Combustion Characteristics

Recommendations:

- Study the process of mixing and combustion of diesel fuel.
- Seek to speed up the slow diesel burning process at the end of the combustion stroke.
- Experiment with stratified charge ignition engines to approach diesel performance and provide multifuel use.

Discussion:

The processes of mixing and combustion, particularly of diesel fuel, must be understood so that both particulates and NO_x (nitrous oxides) emissions can be simultaneously reduced. Failure to solve this problem may reduce the opportunities to use high-efficiency diesel engines as progressively stricter pollution standards are enacted.

Combustion irreversibilities consume about 30 percent of the energy availability in diesel fuel. A means to speed up the comparatively slow burning process at the end of the diesel combustion stroke would improve the overall diesel efficiency. This is because the late burning supplies heat energy at a temperature lower than that supplied by early burning.

Stratified charge ignition engines, which approach diesel performance, offer the potential of multifuel use, including ethanol. For example, they would be more tolerant to lower-quality and nonuniform fuels derived from coal than would conventional ignition engines. Although not necessarily a more energy-efficient engine, the stratified charge ignition engine allows for the economic use of domestic fuels rather than imported fuels.

Improvement of Path of Piston

Recommendation:

- Develop a motion transducer that can be introduced between the piston and the flywheel in an Otto or diesel engine.

Discussion:

An approach that has been analyzed theoretically but has yet to be translated into a practical test device is the introduction of a motion transducer between the piston and the flywheel-and-crank of Otto or diesel engines to make the piston follow a path whose time course optimizes the average power. According to theoretical analyses, this would yield 10 to 15 percent more power for the same fuel consumption than would a conventional engine with its piston making an approximately sinusoidal time path. The requisite transducers can be made with shaped cams and possibly with electromagnetic motion transducers. Whether the transducer could be made to reliably withstand the ordinary stresses in the use of an automobile is unknown.

Improvement of Control Within Cycle

Recommendations:

- o Explore variable capacity compressors.
- o Develop improved expansion valves.

Discussion:

In refrigeration cycles, the thermodynamic performance at heat sink temperatures that differ from the design point can be improved by using variable capacity compressors and by improving control of the expansion valves that minimize irreversibilities in the condensor and evaporator at lower refrigerant mass flow rates (Mozurkevich and Berry, 1981). In internal combustion engines, particularly the diesel, major efficiency improvements can be achieved by paying attention to the aerodynamics within the cylinder-piston volume. One approach is to make the compression part of the cycle approximate the common isothermal Brayton cycle.

Improved Materials to Resist Higher Temperatures

Recommendations:

- o Develop high-temperature, high-strength, and machinable ceramics.
- o See recommendations in Special Materials section.

Discussion:

Higher-temperature engines such as turbines and mageto-hydro-dynamic generators offer higher energy efficiency (Larsen and Johnson, 1984). The principal limitations now are in the properties of the materials of the devices. By developing high-temperature, high-strength, machinable, castable, or otherwise formable ceramics, one could operate turbines with the temperature of the incoming gases closer to the flame temperature, thereby increasing the thermal efficiency.

SENSORS AND AUTOMATIC CONTROLS

The advent of the modern computer chip offers outstanding opportunities for controlling the flow of energy in a vast spectrum of processes. As seen in the discussion that follows, the current ability to detect real-time information on field conditions relating to energy use lags far behind the current ability of modern computers and control systems to use the information. While computer ability continues to grow rapidly, the technology for obtaining useful energy input data remains behind.

This subject is discussed within the following research approaches:

- Improved sensor technology
- Models to extend the scope of sensors
- Models in the process loop
- Artificial intelligence, expert systems, and robotics
- Remote sensing/novel applications

Improved Sensor Technology

Recommendation:

- Develop sensors that can function in more stressful environments, such as high temperatures, high-speed moving parts, radiation, and chemical-reactive environments.

Discussion:

There are single computer chips with appreciable data storage and arithmetic capability, affordable microcomputers for use as control logic elements in subsystems, and inexpensive minicomputers for larger data-handling and alarm systems. With these computer hardware capabilities, bold thinking can lead to new energy-saving applications for consumer appliances and industrial systems. Although these systems have become more efficient, further improvements are limited by a single problem whose root is neither the availability of applicable methods of measurement nor the availability of improved sensor technology. The problem is translation of the sensory device from a specialized scientific instrument to a mass-produced commercial or industrial product. The barriers to this can be categorized as environmental, economic, and institutional.

Environmental barriers refer to the working environment of the sensor. Its volume may be limited by mechanical design constraints; it may be asked to perform at extremely high or low temperatures or in hostile chemical environments; and it may be subject to vibrations, accelerations, and so on. The process to be controlled may require such delicate tuning that only a remote sensor is acceptable. For example, it would be desirable to sense in real time the electric charges in lubricants that give early warning of lubricant breakdown. If they could withstand the environmental stresses, such sensors could be linked to sophisticated engine control systems, which could process the sensed parameters and initiate corrective feedback (reduction of speed or addition of lubricants). In other applications, sensors may be called upon to perform in restricted spaces (engines), high-speed moving parts (turbine blades), high-radiation fields (nuclear reactors), or exotic chemical environments (catalyst beds).

Examples of inadequate sensor technology illustrate opportunities for new development. A famous case is the accident at the Three Mile Island nuclear power plant. Although other factors may have contributed to the incident, a key issue was the absence of adequate sensors of the water level in the reactor and water flow in its associated pressurizer. In this case the lack of proper sensors was part of a chain that converted a relatively minor incident into a serious accident. For such situations, it is desirable to develop improved sensors that are linked to control loops in order to increase system efficiency and performance by surveying and modulating routine operation as well as to enhance safety.

Sensors are being called on to perform in very hostile environments. For example, in the low-heat-rejection or adiabatic engine, high temperatures must be measured in an oxidizing or sulfiding environment; this requires protective sheaths or new alloys. It is a long way from the use of an instrument in a controlled laboratory setting to its application in the factory or field. This example involves obvious economic constraints, and probably institutional barriers, but the major problem is that of fitting the sensor into the total process environment.

Institutional barriers include poor information transfer in industry, particularly across professional lines. Conservatism of the designer or regulator, who may be skeptical of the reliability of a novelty, must also be recognized.

Models to Extend the Scope of Sensors

Recommendation:

- Expand research of basic physical processes so that models can be designed for a very wide variety of situations not accessible to sensory devices.

Discussion:

Situations exist for which there is little chance of developing sensors for direct continuous measurement. Examples are:

- mass-temperature-pressure profiles of fuel and oxidant in a combustion chamber and

- steel embrittlement as a result of fast neutron irradiation in a nuclear reactor.

When such information cannot be obtained, control must be based on human intervention, qualitative heuristics, and sheer guesswork. However, the ability to model systems and processes accurately is improving rapidly. In some instances, models have been validated to a point approaching the reliability of a physical law. Such models can supply a control loop with information as valid as that coming directly from a sensor of moderate accuracy. An example of this is the specification of power density throughout a nuclear reactor core from neutronic computations and a limited number of observations on system power and coolant temperature and flow, particularly in boiling water reactors. According to this concept, data from a sensor system are processed by a computer program that is based on a model of the process or device being monitored. The output of the program is then used to control a feedback system, which in turn controls the process or device.

This capability has not yet been developed to full advantage. The use of elaborate models is not part of the traditional control algorithm, and there is institutional reluctance to accept this approach. This is not surprising given that certain industries (nuclear, shipping, utility, building, steel) have been slow to accept modern concepts of automation and tend to resist even now-traditional automation ideas from other sectors. To help in the identification of worthy proposals in this category, it is useful to indicate the characteristics required for good modeling in a process control context:

- Models must be able to accept information from available sensors and reconcile it with ongoing performance evaluation; the irreconcilability of a particular sensor signal with any malfunction in the model should provide an alarm capability, for example, a warning of probable sensor malfunction.
- The information that model-based sensors provide must be of determinable and acceptable accuracy.
- The information must be made available in a timely manner, timeliness being dictated by system dynamics.
- The operation must be feasible with computational equipment that is economically appropriate for the system and job.

Depending on requirements, models will vary in sophistication from detailed representations based on scientific theory and large, well-validated data bases, to semiempirical settings based on correlations and heuristics, to relatively elementary processing of input data. For the semiempirical group, the most likely to be widely used support for the development of specific innovative process descriptions would have very high leverage. The more detailed models can be expected to be used by regulatory agencies or research laboratories, primarily for validating simpler models. Detailed models tend to be neither quick nor cheap to run. There is far more support available at present for detailed modeling, generally considered more "scientific," than for semiempirical studies. Even regarding heat transfer, a field in which semiempirical modeling has long been standard, the recent tendency has been to derive models from first principles. This is not to be decried: detailed modeling is necessary and desirable. However, semiempirical application modeling must not be set aside, because it has a separate and worthwhile rationale. This is connected to the "chaos" approach: processes that are not really stochastic are nevertheless amenable to the powerful and efficient methods of stochastic modeling.

Related problems that generally need to be addressed include specifying the demands for sensor precision, range, and dynamic response. The design of an extremely capable automatic control system is a challenging synthesis problem for each new application. However, a partial analysis of the general state of such problems emphasizes three areas where important breakthroughs may be expected:

1. Novel applications of sensors;
2. Incorporation of system or subsystem models into the loop to correlate sensor information, to supplement it, and to provide predictive power;
3. Use of expert systems to detect conditions requiring an alarm signal for automatic response and human intervention.

Models in the Process Loop

Recommendations:

- Focus research on combustion engines, metal-working equipment, and ceramic formers.
- Study the process of wear on surfaces, reliability of components, and brittleness of metals by using more advanced sensory tools.

Discussion:

An excellent example of an energy-process loop occurs within a nuclear reactor. In nuclear reactors sensor information (temperature, pressures, flows, and neutron and radiation field strengths) is melded with system models to provide information about the state variables: power, reactivity, location and intensity of hot spots, power profiles, isotope concentration profiles, and so forth. The state variables of a process are the parameters required for control. Additional potential applications of "within-loop" models include:

- Melding of sensor information in combustion engines into control of fuel and oxidant flow regimes and local concentrations;
- Metal-working equipment in which the state of the work is monitored and used as a sensor of the state of the tools;
- Ceramic formers in which one can see inside the mold;
- Historical integration of wear on surfaces, reliability analysis of components, brittleness of stressed metals, and other history-dependent phenomena.

In all of these cases, the principal problem is to find the right match between model and computing device to satisfy economic and dynamic (that is, time-scale) constraints.

Artificial Intelligence, Expert Systems, and Robotics

Recommendation:

- Conduct research on integrating all steps in the standard control loop, from sensing through processing to control signal and feedback.

Discussion:

These approaches to automatic control have the potential for improving the efficiency of most industrial processes. With the ability to rapidly respond to system state, a complex operation can be maintained within a prescribed design envelope. A related capability entails giving alarm of potential malfunctions, which are diagnosed by detecting excessive demands on the control system.

The inclusion of computing within the control loop extends these capabilities in several ways. In systems with multiple sensors, self-consistency of the information can be monitored, and potentially erroneous signals can be detected. Information that comes from robust theories or from well-validated empirical models can be incorporated directly into both feedback loops and interpretive routines. Computing can be used for prediction (to avoid future trouble) and for trouble-shooting through the use of expert systems.

A further advance is the use of expert systems on-line, combining computer models with automatic signals and controls. These systems, sometimes called "robots," have great potential utility for diagnosing malfunctions and recommending remedial action. Their use off-line is growing, such as in electronic automobile diagnosis, but on-line use lags. Research is needed at each stage of the standard control loop and for integration, including research on (1) information detection, (2) transmission to computer system, (3) comparison with optimal performance, (4) inference of control requirements, (5) harmonization with control capability, (6) transmission of command signal, (7) control action, and (8) return to information detection (Step 1). Of these conceptual steps, computing devices perform Step 3 as well as is usually required and are extremely useful in Steps 4 and 5. Step 7 is a matter of electro-mechanical-hydraulic-optical design, which is normally considered adequate for the immediate task, except for the regulation that takes the system of sensor and response signals back through the loop again. For example, the detection signal transmission function must be ready for action before the device receives its next control signal. Step 1, information detection, is commonly the limiting factor in designing optimal operations. While automatic controls are a key to improved system efficiency, improved sensor technology is the key to wider use of automatic controls.

Remote Sensing/Novel Applications

Recommendation:

- Experiment with computerized-axial tomography (CAT) in a variety of applications, for example, neutron radiography in metal forming; differential thermometry; laser refraction, diffraction, and scattering for inspection of close tolerances; on-line potentiometry for tracer ion concentration; and description of turbulent eddies within a fluid.
- See recommendations in Building Envelopes section.

Discussion:

Remote sensing technologies usually allow for the measurement of physical and chemical properties without perturbing or otherwise influencing the behavior of the system being measured. These systems detect electromagnetic phenomena from a remote vantage point. For example, CAT scans, based on a variety of techniques including nuclear magnetic resonance, ultrasonics, and radiation, provide an almost magic ability to "see" inside a complex object. CAT has been impressive in the medical field and recently in sensing the earth's crust and mantle. These approaches must surely provide opportunities for extracting useful information for routine on-line use for manufacturing. Examples of CAT applications to be profitably developed include:

- Neutron radiography as an on-line tool in metal forming;
- Laser refraction, diffraction, scattering, and interferometry for inspection of optical properties and checking of close tolerances;
- Differential thermometry, particularly of high-temperature systems (because of rapid heat transfer at high temperatures, large thermal gradients are sensed as small temperature differences);
- On-line potentiometry or other measurement of specific tracer ion concentration to monitor chemical changes;
- Turbulent eddy description within a fluid.

In other areas, such as electron microscopy, where the primary data are insufficient for tomography, other methods of image analysis, "image enhancement" by multiple-scan averaging, and deliberate reduction to discrete degrees of contrast (for example) can yield adequately accurate and useful reconstructions of the desired objects. Such remote sensing methods are capable of probing heretofore inaccessible information. In general, a "What would we really like to know?" approach to sensor development is needed, rather than the current "What can present sensors measure?" approach.

MATERIALS PROCESSING

The term "materials processing" at one time had a very limited meaning, referring specifically to the classical metallurgical operations of mining and extraction of ores, refining of bulk metals and alloys, and final fabrication into usable forms by casting or hot working. Today this same term has a much broader meaning, encompassing such diverse operations as treatments to modify surfaces with radiation and particle beams, rapid solidification of metastable materials, synthesis of materials from chemical (molecular) precursors, and even the shaping of hard, monolithic ceramics. This broader definition of materials processing is the focus of the following discussion.

In the past decade, the skills of the materials scientist have advanced to a stage at which new materials with specific properties can be constructed using new tools such as thin film deposition and ion implantation. The material is no longer a commodity, such as copper or steel, but a high-value-added product more akin to a semiconducting device. It is in this area where the scope for innovation is greatest.

The opportunities include the following:

- Innovation in traditional materials processing
- High-temperature processing

- Surface modification treatments
  - Chemical vapor deposition
  - Laser surface alloying
  - Ion implantation
  - Molecular beam deposition
- Rapid solidification processing
  - Thin-sheet casting
  - Spray forming
- Chemical synthesis
- Shaping of ceramics
- Forest products industry applications

Innovation in Traditional Materials Processing

Recommendations:

- Search for opportunities in mining, extraction, refining, and forming of metals.
- Explore extraction of metals from powdered ores.
- Explore methods for near-net-shape fabrication.
- Explore improved instrumentation, controls, and robotic systems.

Discussion:

The traditional methods of producing metals and alloys from naturally occurring ores are very energy intensive. Mining and crushing operations use considerable mechanical and/or chemical energy as fuel or explosives. Current DOE-sponsored advances in the tribology of cutting tools and in engine technology will improve this situation, but more could be done to explore novel methods of extracting (leaching) the metals from the ore to reduce the requirements for crushing and grinding energy.

Traditional refining processes are inefficient and capital-intensive. If a powdered metal, rather than a bulk casting, is a desired product (as a feed to a near-net-shape compaction and sintering process), then direct reduction of the metal oxide or sulfide (e.g., by hydrogen) will probably be more energy efficient than would the traditional counterpart. Laser and plasma reactions are also feasible direct-reduction routes.

Two related factors lead to energy efficiency in manufacturing materials to their final usable shape. First, as hinted in the previous paragraph, fabrication to a near-net shape conserves energy, and probably materials as well, because recycling is never 100 percent effective. Near-net-shape fabrication processes include powder metallurgy and electromagnetic forming, but there must be others as yet undeveloped. The second factor is productivity or manufacturing efficiency. Obviously, the higher the yield of usable product, the less the energy consumed overall. Efficiency may be increased through (1) better instrumentation and control of processes where the current need is for better sensors that will function reliably in the hostile environment of the process; (2) robotics and automation where a better understanding of the applications of artificial intelligence and expert systems is needed; and (3) inspection (batch and on-line) entailing new and improved methods of nondestructive evaluation, for example, nuclear magnetic resonance and computer-aided tomography, which have been developed for medical diagnostics and show promise as on-line tools for inspecting pores and flaws in fine ceramics.

High-Temperature Processing

Recommendations:

- Experiment with chemical reactions at higher temperatures to exploit increased energy efficiency.
- Explore metal extraction from powdered ores.
- Seek greater thermodynamic efficiency in heat engines.

Discussion:

The potential for processing carried out at temperatures higher than those now used arises from (1) greater thermodynamic efficiencies in heat engines and (2) more efficient chemical reaction processes, when either the equilibrium shifts in the desired direction with increasing temperature, or the rate of a reaction increases and the faster reaction improves the performance of the process. Furthermore, some techniques for materials processes simply cannot be conducted except at very high temperatures.

An example of a potential improvement in a high-temperature reaction is the production of hydrogen from water. The equilibrium of $2H_2OH = 2H_2 + OH_2$ shifts to the right with increasing temperature. If, even in a simple direct thermal decomposition of water, the process could be run at approximately 3,000°K and the products quenched in approximately 10^{-3} seconds, a net stored fuel energy of the produced H_2, per unit of input energy, could reach approximately 5 to 6 percent, probably the optimum for this direct splitting process. To achieve such a hot reacting mixture, one would have to devise a means such as microwave heating to make the flowing, reactive gases considerably hotter than the chamber walls. This is not an unusual demand. It happens all the time in internal combustion engines and could be achieved in a continuous flow reactor as well.

Some industrial processes can occur only at high temperatures, such as sintering of refractory metals like titanium. If one can work with metal powders to fabricate structurally sound objects, then methods to win the metals from their ores in powder form, rather than as ingots, can lead to large reductions in energy demand. A further important consideration is to capture the high-temperature residual heat from such processes for other economic uses, using heat exchanger technology previously discussed.

Surface Modification Treatments

Recommendations:

- Explore chemical vapor deposition for coating of heat exchangers, pipe, reactor vessels, and so forth, for critically stressed materials.
- Explore laser surface alloying at low energy input combined with glazing as a way of surface modification.
- Explore ion beam implantation to increase the range of economic application for small critical components in high-wear situations.
- Explore molecular beam deposition for tailoring the microstructure of composite materials.
- Study the basic physical/chemical processes in all of these approaches.

Discussion:

Surface modification technology, as applied to structural materials, has assumed a prominent position in materials engineering. An extraordinary variety of methods for surface treatment has been devised to deal with specific problems encountered in real-world environments, such as corrosion, erosion, and wear. It is not the Committee's intention to critically review all these processes but merely to highlight some of the new developments that promise to extend the scope and flexibility of surface modification and in thus reduce total energy inputs. The four areas that appear to hold the greatest potential for innovation are chemical vapor deposition, laser surface alloying, ion implantation, and molecular beam deposition. Developments in these areas should have favorable impact on future engineering and process systems by extending their lifetimes and performance capabilities and by increasing energy efficiency in manufacturing (for example, by reducing friction in wire or tube drawing). Application studies are needed as well as fundamental studies.

Chemical Vapor Deposition Chemical vapor deposition (CVD) is a versatile technique for applying protective coatings (both diffusion and overlay coatings) to materials surfaces. Unlike many other coating technologies, CVD can be scaled up, and it does not depend on line-of-sight access to the work-piece surface. Thus it is the preferred coating method for batch processing of complex-shaped parts, such as cutting tools, that are coated routinely with multiple layers of hard ceramic materials. CVD is also an attractive option for coating internal surfaces such as heat exchanger bundles, process piping, and reactor vessels. Such a technology could be an integral part of engineering design in future systems. Thus, critical engineering hardware (for example, the first wall of a fusion reactor) could be designed for periodic reconstruction by CVD techniques.

Laser Surface Alloying Surface melting (glazing) using high-power-density lasers (or electron beams) has been used successfully to modify the surface properties of materials. Although some benefits can be obtained directly from rapid-solidification laser glazing of some materials (for example, high-speed steels), the greatest benefits accrue when glazing is combined with surface alloying. Methods of surface alloying include preplacement of alloying material (powder, electro deposit, and so forth) on the work-piece surface prior to glazing or continuous delivery of alloy powder to the interaction or melt zone during glazing. For example, injection of hard carbide particles into the alloy substrate has been used to develop wear-resistant surfaces for valve seats and bearings. The possibilities for surface alloying treatments, however, have by no means been exhausted. Further work is needed to determine the feasibility of using (1) reactive gases for more convenient surface alloying (for example, carburizing) and (2) gaseous or liquid organometallic precursors for applying ceramic overlay coatings (that is, laser-induced CVD). All these processes make efficient use of the available energy in the focused laser beam because the substrate remains essentially at ambient temperature during processing. Despite the low energy conversion efficiency of electric power to laser energy, the net energy balance in many practical situations is still favorable.

Ion Beam Implantation Ion beam implantation is a powerful technique for modifying the surface structure and properties of materials, but it is limited to relatively small areas of application, on the order of 50 cm^2, and to very thin layers of 2,000 angstroms or less. Because of these limitations in processing, applications have been restricted to surface modification of small, high-performance components such as bearings, seals, and cutting tools. Thus the main thrust of research activities, at least in the structural materials area, has been ion beam surface modification to reduce friction and wear. In this regard, N^+ ion implantation of hard materials, typically at dose levels of 5 x 10^{17} ions/cm^2, has proved to be particularly beneficial, with a factor of 10 or more reduction in wear rates routinely accomplished in bearing and cutting-tool materials.

Another recent development has been the introduction of combined ion implantation and vapor deposition processing, called "ion beam enhanced deposition." This process has great potential as a means to apply hard ceramic coatings (graded in composition, if necessary) to metallic substrates, with a guarantee of good metallurgical bonding between substrate and deposit. An interesting example is the synthesis, under essentially ambient pressure conditions, of cubic boron nitride. This unexpected result has raised questions concerning the applicability of ion beam processing to the synthesis of new classes of metastable superhard materials (for example, diamond), which could find useful application as coatings for punch and die sets and as hardfacings for cutting elements. In this area there is an urgent need for in-depth studies of the mechanisms involved in the actual synthesis of the materials.

Molecular Beam Deposition Molecular beam deposition is one of the most sophisticated techniques available today for tailoring the microstructure of composite materials (metal/metal, metal/ceramic, metal/polymer) on a very fine scale (nanoscale dimensions). A wide range of compositionally modulated semiconductor materials has been produced, and some surprising physical and electronic properties have been uncovered, such as quantum well effects. Much less work has been done on metallic and ceramic materials, but already some interesting effects have been discovered. Remarkable increases in elastic stiffness have been reported for layered structures of nickel and gold, in which the thickness of the individual layers is less than 2 nm. Changes in electrical properties with layer thickness have been reported for modulated structures of nickel and molybdenum; the structures become insulators or nonmetals when the layer thickness is less than one nm. By changing metal type and layer thickness, devices can be generated that combine normal conductivity in the plane of the films with variable conductivity normal to the plane. These findings clearly underscore the importance of materials with nanoscale dimensions.

It has been claimed, with some justification, that "nanoscale solids" are special kinds of materials, with characteristics that are intermediate between conventional crystalline and amorphous (glassy) solids. This is because when the scale of the microstructure is reduced to 1-10 nm, the volume fraction of the incoherent grain boundary interfaces becomes comparable with that of the crystalline regions. The synthesis of nanoscale solids is not limited to molecular beam deposition. Similar results have been obtained by extrusion, rolling, and mechanical milling of dissimilar material combinations, for example, iron-copper (Fe-Cu), copper (C-glass), aluminum-silver chloride (Al-AgCl), aluminum (Al-Teflon), and aluminum-aluminum oxide (Al-Al_2O_3).

Funding is needed in all these areas for application studies, since there is already a good background of basic knowledge. An example of an application is in dies for wire and tube drawing. Considerable energy is expended in such processes. Furthermore, the dies are usually made from cobalt-bonded tungsten carbide. Cobalt is a strategic material, and Zaire, Africa, is almost the sole source of supply. An alternative approach would be to forge the die shape from inexpensive ferro-titanium-carbon alloy and coat the die surfaces with low-friction hard deposits of tantalum-nitrogen-carbon or hafnium-nitrogen-carbon by CVD techniques, laser glazing, or ion beam enhanced deposition, using a vapor deposit of tantalum-hafnium and an ion beam of nitrogen-carbon. In addition, a compositionally modulated overlay coating of a superhard material may be applied by molecular beam deposition. Although such complex surface modification treatments may be relatively expensive, the product has a long life, is free of strategic metals, and if integrated over its lifetime should involve less energy input in its manufacture. More important, it should result in less energy use in the drawing operations. What is needed is an energy balance study, which, if favorable, would be followed by development studies leading to the commercial-scale production of components.

Rapid Solidification Processing

Recommendations:

- Continue research on thin-sheet casting for fabricating many metal shapes.
- Develop new thin-sheet casting methods in the .010- to .050-inch range.
- Develop new applications for thin-sheet casting, such as particle strengthening and fiber reinforcement.
- Explore rapid solidification spray forming of metals and composite materials.
- Explore spray forming to exploit displacement reactions, synthesize multilayered structures, and fabricate complex shapes.

Discussion:

The science and technology of rapid solidification have been the focus of a national effort for about a decade. Major funding commitments have been made by several government agencies, and support by private industry has not been lacking. As a consequence, remarkable progress has been made in our understanding of the fundamentals of rapid solidification processing and the metastable states derived by rapid quenching from the molten state. In addition, much progress has been made in manufacturing technology, including (1) the production and consolidation of rapidly solidified fine powders and (2) the fabrication and utilization of rapidly solidified thin filaments, ribbons, or sheets. In view of this, it may be asked whether there is any need for additional support in this field.

After carefully reviewing the literature, the Committee concluded that at least two areas of opportunity would benefit from additional funding. These are continuous casting of thin sheets suitable for automotive and other applications and rapid solidification spray forming of near-net-shape composite structures. Spray forming of shaped structures has the advantage of combining powder production and consolidation in a single energy-efficient process. There is a need to investigate the fundamentals of spray forming and to determine the feasibility of fabricating shaped composite structures by computer-controlled processing. Continuous thin-sheet casting is an attractive processing concept in that the usable sheet product is formed directly from the melt, which obviates much of today's energy-intensive sheet fabrication technology. Success in planar flow casting of very thin (0.004 inch) sheet products encourages the hope that a similar technology can be devised to produce sheet in the more useful 0.010- to 0.050-inch thickness range. Such sheet stock would have great utility in the fabrication of a broad range of commercial products, including automotive bodies, appliances, and containers.

<u>Thin-Sheet Casting</u> The conversion of molten metal directly into usable solid forms by continuous casting is an important metallurgical concept that has contributed much to reducing energy requirements in metal forming. It has been applied to the fabrication of a wide variety of simple geometrical shapes, such as rods, bars, billets, and tubes. The recent introduction of novel thin-section continuous casting processes, such as melt spinning, melt extraction, and roller quenching, has added a new dimension to continuous casting technology. Thin filaments, ribbons, and sheets can now be produced directly from the melt at very high rates and with uniform thickness in the range 0.001 to 0.005 inch. As is well known, a particular advantage of such thin-section

casting is the very high cooling rates (that is, solidification rates) that can be achieved, which have the important effect of generating uniform, homogeneous microstructures (for example, amorphous solids, microcrystalline materials, and extended solid solution or metastable phases). Successful commercialization of these rapidly solidified materials has been realized in at least two cases: (1) the use of high-aspect-ratio thin filaments as reinforcing elements in castable ceramics and (2) the synthesis of low-melting-point interlayers for brazing purposes. An impending application is the use of thin sheets of amorphous soft magnetic alloys in electric motors and power transformers, where the characteristically low core losses of the materials can be used to advantage.

Although continued research in thin-section casting is sure to give additional payoffs, there is also a need to develop new methods for continuous casting of sheets with thickness in the range of 0.010 to 0.050 inch, because many commercial products are fabricated from sheet stock of these dimensions. Examples include construction materials for automobile bodies, appliances, and containers. Possible approaches that need to be investigated include sequential multilayer planar flow casting of wide sheets and some variation of melt spinning or melt drag processing. Thin-sheet casting could also open the door to new possibilities for particle strengthening and fiber reinforcement and may even permit localization of strengthening, for example, along one edge of the sheet, as is required in composite saw blade manufacture. In multilayer planar flow casting, changing the feed during the last few incremental solidification steps could be a straightforward method for making cladded material.

Spray Forming In the fabrication of shaped parts by conventional powder metallurgy processing, the synthesis and consolidation of powder particles are usually carried out as two separate operations. An obvious improvement to this technology that would reduce energy and manufacturing costs would be to combine particle production and consolidation in a single operation. The only process available today that has this capability is spray forming, which is being developed both in the United Kingdom and Sweden. Spray forming takes advantage of the fact that in any controlled gas atomization process there is a well-defined region in the atomized stream where most of the particles are in the semisolid, or mushy, condition. When a mold is placed at this location, it quickly fills with spray-consolidated material. The microstructure is extremely fine and homogeneous by virtue of the fact that it is formed by aggregation of mushy particles and experiences moderate rates of solidification. The resulting molded body can be forged into complex shapes while still in the hot, as-deposited condition. Other simple geometrical shapes can be made directly by spray forming, for example, tubular shapes, in which a rotating/

reciprocating mandrel is used as a rigid support for building up of the cast structure. Very high rates of deposition have been demonstrated, and experimental tubes of practical dimensions have been produced in relatively short times. Composite structures, such as bimetallic tubulars, have also been spray formed, making use of two separate atomizing units.

Despite the demonstrated advantages of spray forming as a low-cost, energy-efficient process, little or no development work is being done in the United States. This situation should be remedied, and perhaps as a first step some action should be taken to stimulate the necessary research at university or national laboratories. Some opportunity areas that merit investigation are (1) rapid solidification spray forming of composite materials, both particle-strengthened and whisker-reinforced; (2) spray forming under conditions designed to exploit displacement reactions (that is, two reactive spray deposition sources); (3) synthesis of multilayered structures through use of multiple atomizing units; and (4) fabrication of complex shapes such as valve housings and exhaust manifolds by computerized preprogrammed spray forming.

Chemical Synthesis

Recommendations:

- Conduct research to address critical fundamental issues related to the design and synthesis of molecular precursors.
- Conduct research on optimal reaction-phase decomposition pathways leading to the final consolidated net-shape product.

Discussion:

Chemical approaches to materials synthesis are rapidly gaining acceptance in the materials field for two reasons. First, because they are more direct routes to materials synthesis than are conventional methods, energy costs in processing tend to be much lower, and, correspondingly, overall manufacturing costs are much less. Second, because the material is built up from molecular dimensions, it is possible to control the microstructure on an unprecedented fine scale and with complete uniformity of structure and composition in the finished product. This is in marked contrast to conventional materials processing, in which the final product inherits much of the segregation and microstructural heterogeneity characteristic of the initial cast ingot.

Another consequence of improved flexibility in microstructural control is that it permits more opportunities for trade-offs in such critical properties as strength and fracture toughness. As a general rule, the finer and more homogeneous the microstructure, the better the overall properties, and the greater the potential for optimization of properties.

Chemical synthetic routes to materials processing have been used with great success in the nuclear materials industry. Mixed carbides and oxides of fissionable materials are routinely produced by coprecipitation from complex salt solutions. Chemical vapor deposition conducted in a fluidized bed has been used to coat the ceramic particles with thin layers of metals prior to consolidation into pellets on other usable forms. A similar technology, sol gel technology, has been developed for the synthesis of ceramic materials for structural and electronic application and represents the state of the art in the field.

Current research is focused on extending the range of applicability of chemical synthetic routes to materials processing. Of particular interest are the attempts now being made to synthesize novel transformation-toughened ceramics and the new classes of ultrarefined metal/ceramic composites, including the technologically important cermets.

Chemical approaches to materials synthesis are energy efficient and applicable to a broad range of materials. Although considerable effort has been devoted to the chemical synthesis of mixed carbides and oxides, much less attention appears to have been given to the synthesis of advanced transformation-toughened ceramics and metal/ceramic composites, such as cermets. Research is needed to address critical fundamental issues relating to composite synthesis, including the design and synthesis of the complex molecular precursors and studies of the optimal reaction-phase decomposition pathways leading to the final, consolidated, net-shape product.

Shaping of Ceramics

Recommendations:

- Explore photolithographic techniques coupled with dry etching.
- Construct wafers by laser chemical vapor deposition.
- Explore microwave heating for the diffusion bonding step.

Discussion:

In a number of energy systems and devices it is necessary to form ceramics into complex shapes. Obviously, it is both energy efficient and cheaper to form the final shape by nonabrasive methods. These have the added benefit of minimizing flaws that could initiate failure modes.

Among the possible forming methods that can be considered are photolithographic techniques, coupled with dry etching to remove material from unmasked areas. When applied to thin-sheet material, the resulting photo-etched wafers can have extremely complex geometries. Thus, by stacking appropriately etched wafers in a predetermined arrangement almost any desired configuration of shaped solid or porous ceramic can be produced. To join together such a stacked array, various options are available, including transient liquid-phase diffusion bonding, which makes use of very thin photo-etched ceramic eutectic interlayers for diffusion bonding purposes. At the bonding temperature, the eutectic melts and wets the contacting surfaces, the melt depressant in the eutectic diffuses away into the substrate, and the solid joint is gradually formed under isothermal conditions.

Such a technology would permit the fabrication of advanced ceramic heat exchangers, in which the exchange of heat between the working fluids occurs within interconnecting networks of internal passages incorporated within the ceramic body. Because of the great versatility of the photo-etching process, not only can most any desired configuration of internal passages be built into the ceramic body, but also the end points of the passages can be linked together in common manifolds, which would facilitate ingress and egress of the working fluids. Such a technology has already been demonstrated in the fabrication of advanced air-cooled superalloy turbine blades, which combine conventional internal convective cooling with transpiration or film cooling. The air-cooling passages, including both internal and surface-connected passages, are built into the original multilayer structure by photo etching.

Another approach would be to construct the wafers by laser-assisted chemical vapor deposition, for example, by actual deposition on unmasked areas. Alternatively, tape casting could be used to fabricate the initial ceramic sheet material before dry chemical etching to produce the desired wafer geometry. Microwave heat might offer some advantages for the diffusion bonding step in the fabrication process.

In summary, a number of novel techniques give promise of being able to produce final-shape ceramic components of complex design (for example, ceramic heat exchangers). Photolithography and dry etching of thin tape-cast ceramic sheets, with final joining by transient liquid phase diffusion "brazing," should lead to the production of a wide range of complex ceramic components in an energy efficient manner. Such processes require exploratory studies and economic analysis before more extensive R&D programs are justified.

Forest Products Industry Applications

Recommendation:

- Seek to apply many of the materials-procesing innovations described in this section to energy-intensive materials industries, such as forest products.

Discussion:

This is an example of a very energy-intensive materials-processing industry with many applications that can benefit from research into more energy-efficient methods. These applications include the following:

- Use of the enormous low-grade heat energy in gaseous and liquid effluent
- Drying of particles, lumber, paper, and pulp
- Comminution of wood
- Process control, including new sensor development, in all micro and macro (millwide) processes
- Papermaking by dry processes
- Cascading of energy from high levels to ambient (all aspects of cogeneration)
- Improved engines
- Improved combustion technology (for example, Sandia Program)
- Tribology
- Log trucks fuels and efficiency
- Gasification of wood for lime kilns, boiler, and process use

These areas clearly provide opportunities to apply the technologies discussed in this and other sections. Innovation in this industry is one of the keys to energy efficiency in buildings, which is discussed later.

SPECIAL MATERIALS

A broad range of special materials have been developed that have specific properties that make them unusually suited for applications in highly leveraged, energy-conserving situations. The more important of these are discussed below. This list is by no means exhaustive, but it serves to illustrate the ways in which special materials can play a crucial role in the design and construction of energy-conserving devices and systems. The following topics are discussed:

- Macro-defect-free hydraulic cements
- High-performance ceramics

- o Advanced alloys
- o Superconducting devices
- o Shape-memory alloys
- o Application of special materials to building construction
- o Application of special materials to infrastructure

Macro-Defect-Free Hydraulic Cements

Recommendations:

- o Conduct research to determine the structure-property relationship.
- o Conduct research to define the nature of interactions between polymer additives and cement matrix.
- o Explore applications using various materials, such as nylon, iron powder, and organic fibers, to produce special properties such as high impact resistance and screening of electromagnetic radiation.

Discussion:

Hydraulic cements are manufactured on a large scale worldwide (approximately one billion tons per year) from readily available minerals. Compared with metals and plastics, they are easier to produce and are inexpensive in terms of energy costs. Recently, significant advances have been made in the preparation of a strong material from hydraulic cement that have extended the range of applicability of this complex inorganic material. This new material, which is virtually free of macroscopic porosity, is called "macro-defect-free (MDF) cement." MDF cement is approximately 10 times stronger in tensile strength than ordinary cement, and its impact resistance or toughness is comparable to that of cast iron. It is also impermeable to water, gas, and other fluids, so reinforcing metals do not corrode, and spalling does not occur.

With sufficient water added to make it castable, ordinary cement is made by casting. In the preparation of MDF cement, the water content is greatly reduced (typically to 10 to 20 percent by weight), and a small amount of water-soluble polymer (for example, polyacrylate or polyvinyl alcohol) is added. Mixing is accomplished in a twin-roller mill, and subsequent processing is carried out by techniques common in the plastics industry, such as injection molding, sheet rolling, and extrusion. Hardening of the shaped product can be greatly accelerated by a low temperature (100°C) curing treatment. The final product needs little or no machining, and its properties can be tailored to specific applications by adding particles or fibers. Unlike ceramics, the toughness of MDF cement can be further enhanced by reinforcement with polymer fibers, such as nylon and Kevlar.

The new MDF cements are interesting not only because of their good mechanical properties and formability, as demonstrated by the fabrication of a cement spring, but also because of their attractive appearance and novel properties. At low temperatures, mechanical properties are retained that together with low permeability to gases suggest cryogenic applications. MDF cements have excellent acoustic damping properties, and stereo speaker cabinets and turntables made from these materials are in commercial production. Materials reinforced with organic fibers, such as nylon, exhibit high impact resistance, which suggests their use as armor. Filling the MDF cement paste with iron powder creates a material that is able to screen against electromagnetic radiation. Many other applications in the civil engineering field are suggested by the unique combination of properties displayed by these new materials. High wear resistance and low permeability of MDF cements make them attractive candidate materials for rehabilitation of the nation's infrastructure, as well as for building construction purposes.

Most of the current research on MDF cements is being carried out by Imperial Chemical Industry, Oxford University, and Imperial College in the United Kingdom, where research on MDF cements has high priority. Research at Brookhaven National Laboratory on polymer cement was carried out in the 1970s, but has since been terminated. Recent publication of some of the more interesting research findings has aroused great interest in the United States. New research programs are being initiated and funding sources sought. Much research remains to be done to determine structure/property relationships in MDF cements and to define the nature of the interactions between the polymer additives and the cement matrix. The durability of MDF cements over the long term also needs to be investigated. Such work could be performed at the national laboratories or at universities with a proven track record in cement research.

In summary, MDF cements are attractive materials for construction, in that they are stronger and tougher than ordinary cements. They are also nontoxic, nonflammable, and environmentally benign materials that are possible replacements for many plastics in use today, and may someday even replace metals. U.S. research in this technologically important field needs to be stimulated. Special attention should be given where the potential for innovation is great, that is, composites based on MDF cements.

High-Performance Ceramics

Recommendations:

- Use computerized axial tomography to achieve better control of material shape.
- Use transformation toughening agents to strengthen the ceramic body.

- Produce ceramic powders by laser or by radio-frequency plasma pyrolysis of molecular precursors to produce low-porosity ceramics. o Explore incorporation of strong fibers into the ceramic body to inhibit cracking.
- Perform optimization and scale-up studies to better understand the fundamental processes named above.
- Continue evaluation and testing of advanced materials in gas turbine and diesel engines.
- Perform research on composite manufacture, aimed at reducing synthesis to a continuous-flow, chemical-engineering-type process in order to reduce manufacturing costs.

Discussion:

In the past decade, growing interest in the development of more efficient automotive engines has provided a strong impetus to develop ceramics for high temperature structural applications. Some structural ceramics can now withstand temperatures as high as 1,400°C, whereas even the best of the superalloys cannot be used much above approximately 1,000°C. The DOE currently supports two large demonstration projects to develop ceramic-based gas turbine engines for automobiles, and the U.S. Army is funding an effort to develop ceramic-based adiabatic diesel engines for heavy duty commercial trucks.

Apart from their heat resistance, ceramics have other advantages over metals, including high hardness and strength at elevated temperatures; resistance to oxidation, hot corrosion, and erosion; and relatively low density. The fact that some structural ceramics weigh only approximately 40 percent as much as metals is important in aircraft, missile, and spacecraft applications, in which reduced weight conserves fuel. Some ceramics also exhibit low coefficient of friction, high compressive strength, and wear resistance, making them ideal candidate materials for high-performance bearings and other mechanical components.

Despite their many virtues, however, the use of ceramics in many applications has been limited because of their susceptibility to sudden catastrophic fracture. Ceramics have other shortcomings besides brittleness. For example, they are much more difficult to fabricate into complex shapes than metals, and expensive grinding may be necessary to produce a final product. Joining ceramic parts to one another is another difficulty. In addition, ing production ceramics may develop essentially undetectable flaws that, by acting as stress concentrators, cause a part to fracture unexpectedly. In such cases flaw detection by computerized axial tomography (discussed in the Sensors and Novel Applications section) would be of great assistance to researchers.

In recent years, the focus in ceramics research has been on developing materials with greatly improved facture toughness. One approach is to strengthen the ceramic body by transformation toughening agents. An example is the incorporation of approximately 15 percent (by volume) of finely divided tetragonal zirconium oxide (ZrO_2) particles into an aluminum oxide (Al_2O_3) matrix. When cracking occurs in the Al_2O_3 matrix, the resulting stresses locally allow the ZrO_2 particles to transform to the monoclinic form, thus impeding further cracking. Transformation toughened ceramics have replaced conventional ceramics in cutting tools and in abrasives for metal machining and grinding operations, and some advanced materials are being tested in gas turbines and diesel engines.

Another approach is to reduce the number, density, and size of crack-initiating flaws by making the ceramic from submicron, monosized spherical particles, produced by laser or radio frequency (RF) plasma pyrolysis from molecular precursors. When such particles are formed into dense, close-packed ordered arrays, they can be sintered at relatively low temperatures to produce a ceramic with very little porosity, and with a minimum of small cracks that could develop into larger cracks when the ceramic is later subjected to stress. Reaction-bonded silicon nitride ceramic parts recently fabricated from laser-synthesized powders have shown greatly improved mechanical properties (particularly strength and fracture toughness).

Yet another approach is to inhibit cracking of ceramics by incorporating within them a high-volume fraction (30 to 60 percent by volume) of strong fibers. To be effective, the fibers should have aspect ratios greater than about 50 and should be distributed uniformly throughout the matrix. Lithium aluminosilicate glass-ceramic reinforced with approximately 50 percent (by volume) of silicon carbide (SiC) fibers exhibits excellent mechanical properties, including fracture toughness, at temperatures up to 1,000°C and is a possible replacement for high temperature alloys in gas turbine and diesel engines. Elemental silicon reinforced with SiC fibers has also been used experimentally in a combustion chamber operating at 1,350°C.

Funding in these areas is needed for process optimization and scale-up studies, since many of the critical fundamental issues have been resolved. In the area of laser or RF plasma synthesis of ultrafine/ultrapure powders, the most pressing need is for a realistic manufacturing cost analysis. If the economics look favorable, the highest priority should be given to the construction of a pilot plant unit capable of producing bulk quantities of powders for test purposes.

On the other hand, in the area of transformation toughening of ceramics, the most important need is for continued evaluation and testing of advanced materials in both gas turbine and diesel engines. There is little doubt that the economics will be favorable in this case, because successful commercialization of ceramic materials for cutting tools and abrasives has already been achieved.

In the area of ceramic composites, the overriding concern is the high cost of manufacture. This is a consequence of the fact that current processing involves a complex sequence of operations that, even if automated, would not significantly reduce overall manufacturing costs. What is needed here, and indeed in the whole field of composites, is a radical new approach to composite manufacture that would essentially reduce synthesis to a continuous-flow, chemical engineering-type process. Although this may be difficult to achieve, perhaps a well-conceived request for research proposals might uncover some creative concepts that would merit funding.

In support of ongoing programs to develop ceramic-based engines for automobiles and trucks, there is a need for continued testing of advanced ceramics as they become available, including the new laser-synthesized materials produced from ultrafine/ultrapure powders. In the ceramic composites area, it is recommended that serious consideration be given to initiating studies of new methods of composite fabrication that could sharply reduce manufacturing costs.

Advanced Alloys

Recommendations:

- Seek a potentially new class of superalloys through controlled thermal decomposition of homogeneous supersaturated alloys to create complex three-phase superalloy composites.
- Seek to replace titanium alloys with high-specific-strength aluminum alloys and composite materials for cooler compressors and fan sections of engines.
- Explore rapid solidification of titanium-base alloys to obtain desired particle-strengthened structure.
- Explore the synthesis of inert-particle dispersion-strengthened alloys by reaction processing for titanium alloys (this can be coupled with a broader spray deposition initiative).

Discussion:

Although much of the interest in new materials for the next generation of land-based gas turbine and diesel engines has focused on advanced ceramics, in aircraft gas turbine engines a much more conservative materials design philosophy has prevailed. Thus today, as in the past, nickel-base superalloys of particular crystal structure are the materials of choice for the hottest parts of the engine. However, the performance capabilities of these alloys have not remained unchanged over the years. On the contrary, continuing development in the coupled areas of alloy design and processing has resulted in steady improvements in the high temperature capabilities of these alloys. The evolution of nickel-base superalloy technology has been impressive, with advances in both directional solidification and powder metallurgy representing two outstanding processing achievements. The high point in directional solidification casting technology was the introduction of cast-to-size single-crystal superalloy turbine blades with specific crystallographic orientation. This development is now progressing through new alloys that have been designed specifically for single-crystal application, including a new class of filamentary reinforced eutectic superalloys, which promises to further increase the metal temperature capability of the superalloys.

In turbine disc technology, powder metallurgy processing of nickel-base superalloys (and specifically the superplastic forging process as applied to the consolidated powder product) has emerged as the most enduring innovation. Hot isostatic pressing of near-net shapes has not yet lived up to expectations because of problems associated with the detection and control of internal flaws within the consolidated product.

Current research on nickel-base superalloys has as its focus the further optimization of the microstructure of precisely oriented single crystals that have been homogenized by high temperature annealing. A turning point in this research came with the discovery that stress-induced changes in the morphology, at least in large negative lattice misfit in the crystal structures of the alloys, can exert a profound influence on creep properties. In one experiment, a homogeneous single-crystal superalloy, having about a 75°C advantage in metal temperature capability, was found. A related but largely ignored finding was the reported solid-state precipitation of nitrous tantalum (Ni_3Ta) in alloys supersaturated with respect to tantalum. The resulting structure is a three-phase composite, in which the conventional crystalline atomic structure is boxed in by a rigid three-dimensional structure of thin lamellae of Ni_3Ta. Complex three-phase superalloy composites of this type, formed by controlled thermal decomposition of homogeneous, supersaturated alloys, represent a potentially new class of single-crystal superalloys which promise to further extend the performance capabilities of these materials. Since metal temperature capability in the high temperature section of the engine is the critical design parameter, which largely controls fuel efficiency, there is a large incentive for pursuing this new line of research. Work similar to this is currently being sponsored by the ECUT program on nickle aluminide (Oak Ridge National Laboratory, 1985).

Research on materials for the cooler, compressor, and fan sections of the engine continues to focus on titanium-base alloys. However, there is also renewed interest in the possible replacement of titanium alloys with high-specific-strength aluminum alloys and composite materials. Certain rapidly solidified aluminum alloys are candidate materials for the low compressor section of the engine, whereas high-performance fiber-reinforced composites--such as, graphite/epoxy, graphite/polyimide, and boron/aluminum--look attractive for the fan section of the engine. Rapid solidification of titanium-base alloys appears to be a promising line of research. The goal here is to achieve phase decomposition strengthening by rapid solidification to produce a supersaturated solid solution, followed by aging to obtain the desired particle-strengthened structure.

Another line of research in titanium alloys, which has been considered but not seriously pursued, is the synthesis of inert-particle dispersion-strengthened alloys by displacement reaction processing. The idea is to use two different atomization sources and combine them into a single intimately mixed spray-deposited product. Subsequent annealing results in solid-state reactions that produce the desired optimal distribution of inert particles in the titanium alloy matrix. This is an area of needed research that lacks funding and that could be coupled with a much broader spray deposition initiative.

Superconducting Devices

Recommendations:

- Seek to develop materials with properties superior to niobium titanium.
- Explore specific applications, including the next-generation high-energy accelerator, advanced high-field high-uniformity magnets, and magnetic levitation transport.
- Seek to develop a stable ductile material that becomes a superconductor above the boiling point of hydrogen.
- Explore the application of new materials, such as thin-film niobium nitride, and several organic superconductors.

Discussion:

From the perspective of energy conservation, superconducting devices are virtually without peer--at least in principle. Superconducting magnets, motors, generators, and transmission lines have the potential to operate without loss, and in actual practice they lead to enormous energy reductions. By way of example, the superconducting high-energy accelerator at the Fermi Laboratory operates with a total power of approximately 10 percent of what would be required if conventional magnets were used. Areas with promise include development of practical materials with properties superior to niobium titanium; specific technical applications such as the next-generation high-energy physics accelerator (the Superconducting Super Collider [SSC]); advanced high-field, high-uniformity magnets; and, possibly, a magnetically levitated high-speed transportation system.

However, commercial applications in ore separation, scrap sorting, waste disposal, transportation (for example, levitated trains and electrical transmission lines) have not developed as rapidly as was once predicted. This is because of cost and the slow buildup of the industrial capability, including the costly liquified helium technology. A number of DOE studies have been performed on superconducting transmission lines and storage devices. The economics and energy price structure are currently unfavorable to these concepts but will probably not remain so over the next several decades. The goal of developing a ductile stable material that becomes a superconductor above the boiling point of liquid hydrogen remains elusive; obviously it would be extremely valuable if it were attained. The range of available superconductors has increased, and their potential should be explored, if only for their possible application in fusion reactors. Two examples of new materials are (1) thin-film niobium nitride (Nbn) made by vapor deposition techniques, which has a high critical field (above 24 tesla--a unit of magnetic intensity) probably caused by a microstructure that has many effective flux-pinning sites; and (2) organic superconductors based on tetra-methyl-tetra-selena-fulvalene with halide or oxide radicals attached and bis-ethylene-dithia-tetra-thia-fulvalene-tetra-thia-fulvalene with comparable radicals. The latter are specific organic compounds that crystallize into highly nonisotropic forms, so they conduct in one dimension and insulate in another. Such organics, which contain sulfur or selenium, have metal-semiconductor transitions below room temperature and are often superconducting under a pressure of a few kilobars at temperatures near $2^{o}K$; one or two are superconducting at ambient pressure. The structures are becoming understood and theoretical analyses being made of the electronic behavior of these compounds, and this will undoubtedly lead to the synthesis of materials with more favorable properties. Their applications are a matter of speculation at present, but the time is ripe for scoping studies leading to specific applications in energy-related systems.

In summary, new high-field superconductors for fusion energy and other applications are possible through thin-film coating techniques. Vapor deposition of Nbn produces a very-high-field superconductor that needs to be developed into engineering components. Organic superconductors are at an even earlier stage of development, but they have great promise. Funding is needed to exploit these materials into new energy-saving applications.

Shape-Memory Alloys

Recommendation:

- Develop new shape alloys with higher transformation temperatures for application to more efficient energy conversion devices.

Discussion:

The well-known nitinol alloys have been used to make low-temperature energy conversion devices. Because their transformation temperatures are near room temperature ($0^{o}C$ to $100^{o}C$), the conversion efficiencies of these engines are very low (below 2 percent). The development of new shape-memory alloys with higher transformation temperatures could lead to a new class of more efficient energy conversion devices that can operate on small thermal gradients, thereby effectively using low-grade waste heat. These would, of course, have to be capable of being fabricated and should be resistant to their operating environment.

Application of Special Materials to Building Construction

Recommendations:

- Research should be directed to improving the properties of wood.
- Apply computer-aided design and computer-assisted manufacturer techniques to the lumber industry.
- Apply macro-defect-free cements to the construction industry.
- See recommendations in Building Envelopes section.

Discussion:

In buildings, energy and resource economies may be possible through use of improved wood products as substitutes for concrete and steel. Because composites of wood and metals or polymers have greater structural strength than normal timber-sufficient strength, they can be considered as substitutes for reinforced concrete or steel in certain structures. Even in the use of ordinary wood, improvements are possible through (1) the development of fast-growing trees that replace depletion at the cost of only sunlight and water; (2) development of improved preservatives to fight boring insects, fungi, and bacteria and replace polluting and toxic formulations; (3) the use of advanced manufacturing technologies (automation, computer-aided design and computer-assisted manufacturer, and so forth) in the lumber industry to improve productivity and reduce energy consumption.

Additional opportunities relate to the use of macro-defect-free cements, as discussed earlier in this section.

Application of Special Materials to Infrastructure

Recommendations:

- Develop advanced procedures for repairing roads using on-site melting and reforming.
- Develop the use of additives, such as fiberglass, to improve durability of roads.
- Study and develop macro-defect-free (MDF) cements and improved asphalts.
- Develop coating and relining techniques for conduits and tunnels using catalytically induced polymerization of fluid additives.

Discussion:

The nation's infrastructure of highways, bridges, tunnels, and other public works is progressively suffering from disrepair because of systematic underinvestment and higher than intended utilization levels. Highways, for example, are degenerating at an alarming rate as a consequence of high volumes of traffic, heavy loads, great use of salts for de-icing, and low levels of investment. This deterioration is expected to continue for some years because of efforts at both state and federal levels to hold down discretionary spending. This means the problem will exacerbate before the nation faces the need for action. Thus there should be sufficient lead time to develop materials technologies for refurbishing the infrastructure that are both less costly to apply and more likely to give durable results. These will be less energy intensive in their initial application and, through better performance, will substantially reduce energy use associated with traffic and repairs.

Highway Repair Innovation

The rapid deterioration of the nation's highway system provides an opportunity for innovative energy-saving approaches to both highway repair procedures and roadbed materials. The development of on-site procedures for remelting and upgrading of asphalt roadbeds is highly desirable. The use of additives such as fiberglass, ground-up discarded tires, or other materials to give the roadbed more strength, greater durability, nonskid characteristics, and other desirable properties would be conducive to energy savings.

In-Situ Repair Techniques Other examples of infrastructure needs in the public and private sectors include efficient, energy-saving refurbishment techniques for reconstruction and preservation of bridges and tunnels; for restoration of the integrity of underground water, gas, and oil pipelines; and for reconstruction of large fixed industrial facilities with minimal disruption of plant operations. Because the investments in all of the above facilities are so enormous, there is a considerable premium to be earned from the development and application of improved in-situ repair techniques. The cost of creating duplicate facilities or disrupting infrastructure functions whether a processing plant or a critical bridge or highway, is so great that there should be tremendous incentives to develop quick, easy-to-apply, in-situ techniques and ensure that the durability of the repair is greater than that of current techniques.

Infrastructure Research Opportunities Specific areas of opportunity worth consideration for research are (1) reinforced cements and concretes, which are capable of lasting perhaps 50 years even in the face of heavy vehicular traffic and aggravated salt corrosion and which may incorporate fiber (glass, plastic, or elastomer) reinforcement to enhance strength and traction (in this area MDF cement offers real advantages because of its high strength and impermeability to fluids); (2) improved asphalts, which reduce water penetration by making a more complete bond with the gravel subsurface, are able to withstand heavier loads, and are capable (possibly with microwave heating) of being repaired in place quickly without the need for additional material; (3) chemical coating materials, which when added to the contents of a pipeline form an impermeable chemical bond on the walls, thus repairing leaks; (4) relining techniques for underground piping, using catalytically induced polymerization of fluid additives; and (5) advanced patching materials and techniques for road surfaces.

BUILDING ENVELOPES

Energy consumption in the building sector accounts for approximately 36 percent of the total U.S. energy consumption. Moreover, in the last decade, the building sector's share of energy consumption has increased relative to the share of other sectors; more than 60 percent of the electricity produced in the United States is consumed within buildings.

The lack of rapid progress in the building area is surprising, at first glance, given the numerous demonstrations of superinsulated and solar-augmented structures that have appeared in the United States and overseas. The use of these concepts has also been encouraged by special federal and state tax incentives.

It is difficult to promote conservation in the building sector. To begin with, the building stock existing is diverse and has a long lifetime. More than half of the building stock existing early in the next century will consist of buildings in existence today. This is in sharp contrast to the transportation field, where the average life of an automobile is roughly one decade. There is a proliferation of differing local building codes that any new or retrofit construction must meet. These conservative codes contain a strong bias against new materials and innovations in construction techniques.

Futhermore, builders tend to be local, and the housing sector is dominated by small firms that use low-capital-intensive methods of construction. The only nationwide companies in the field are building material manufacturers, and these are not vertically integrated; each company tends to concentrate on a certain class of materials, such as insulation, wood structural products, plumbing, or appliances. Similar fragmentation occurs in the commercial buildings field and is compounded by restrictive union practices. Finally, the decisions on technology affecting energy use are not made by the end user. They are made by the developer and the architect, who have a bias against decisions that increase the capital investment in a way that cannot be recaptured.

All of these factors tend to limit the easy adoption of innovative technologies. Clearly, many of the roadblocks are institutional. However, there is a need to develop technologies appropriate to the U.S. building sector and to understand the basic physics underlying their concepts so they can be properly applied. Equally important is the need for convenient and reliable analytical methods that will allow practitioners to design and construct buildings using the new technologies.

In approaching building envelopes, it is useful to distinguish between commercial and residential markets, because each has its own unique pattern of energy use and management. Accordingly, this section is organized as follows:

- Residential structures
    - Composite materials
    - New technologies for windows
    - Insulation and sealing of appliances
    - Interior wall insulation panels
- Commercial structures
    - Redistribution of light
    - Redistribution of thermal energy
    - Innovative design with new materials
    - Circulation of air and prediction of hazards
- Whole building research by integrating elements

Residential Structures

Recommendations:

- Develop composite materials such as oriented strand board, stressed skin structures with foam cores, and fiber-reinforced materials.
- Conduct research on material properties of building envelopes in the presence of hazards such as fire, flood, and earthquake.
- Develop commercial window materials with properties such as infrared relfectivity and improved resistance to heat transfer; explore the use of sealed window gaps, using low-conductivity gases or vacuums.
- Explore new insulation concepts, such as microfine powders for use in appliances.
- Develop inexpensive and effective interior wall insulation panels.

Discussion:

Residential buildings are particularly sensitive to the insulating levels of the exterior envelope. New structural technologies in which structural insulating functions (possibly with passive solar characteristics) are integrated should be particularly beneficial. Improved retrofit techniques to increase insulating levels are needed to solve the problems of chemical vapor contamination and excess costs.

Composite Materials For new housing, composite materials technology offers to meet the need for cost-effective and energy-efficient structures. Composite materials can combine structural and insulating functions in a single lightweight panel. Initially, they will be used in manufactured homes. The new composite structures range from oriented strand board to stressed skin structures with foam cores. Fiber-reinforced materials and honeycomb composites may also be appropriate. Earlier negative experience with programs such as Operation Breakthrough (a federal program of the 1960s to reduce housing costs through automation) illustrated that the embodiment of the new technology must be appropriate for the U.S. building field before it will make a substantial impact. Composite materials made with the precision and cost typical of the aerospace industry will be inappropriate to this application. In the case of composite materials, the structure must be above all less costly than alternate structures. The subassemblies must comprise a standard lightweight building block set so that differing designs can be easily assembled from combinations of the standard set.

Flexible joining methods are needed to deal with the inevitable large tolerances produced by the semiskilled building labor force.

The materials and composite system must meet the codes and standards for load bearing, earthquake protection, and fire and health hazards. Corollary research programs are urgently needed in many of these fields to update test methodologies and the basic understanding of properties so that new materials can be rationally evaluated. For example, the hazard caused by pollutants given off during combustion of plastic materials vis-a-vis wood or other traditional materials is the subject of considerable controversy.

New Technologies for Windows New technologies for windows promise a substantial increase in R values. These range from infrared reflective, visible transmissive coatings for windows to submicro aerogel materials that act to inhibit convective and conductive heat transfer. The use of lower-conductivity gases, or, ultimately, vacuums in sealed window gaps, should produce higher R values for window areas. Research on methods to support the overpressure on vacuum panels without glass distortion and on reliable means of sealing that do not contribute substantial thermal short circuits needs to be encouraged.

Insulation and Sealing of Appliances Better insulation and sealing systems for appliances can produce appreciable savings. Use of refrigerators with an R-20 insulation, along with other appropriate improvements, could save the United States as much as one quad of energy per year. New insulation concepts, such as microfine powders in evacuated panels, have the potential of reaching these insulation levels with modest thicknesses, for example, as little as one inch. The insulating values of foam could be increased by as much as 50 percent by the use of thermal radiation inhibitors and the inclusion of vacuum subvolumes. The useful R values of closed-cell foam insulation that is used for exterior wall sheathing could be increased one-third by the development of facing methods that prevent the diffusion of air into the insulation.

Interior Wall Insulation Panels Upgrading the energy efficiency of existing housing requires innovative technological solutions. The addition of insulation to existing wall cavities is expensive, is difficult to inspect, and may lead to moisture damage of the building structure. A thin insulation panel with a high R value that could be installed on interior walls by homeowners would be a preferable technique. Such insulation must not create a fire hazard or emit harmful gases. Present urethane and isocyanate foam panels cannot be used for such an application without an interior wall to act as a fire barrier. Possibly newer closed-cell foams (such as phenolic foams) can meet these requirements.

Commercial Structures

Recommendations:

- o Develop new design concepts to improve the distribution of solar-source lighting within a building.
- o Develop energy transfer systems to redistribute heat within a building for optimal interior temperature control.
- o Promote exploration of new design concepts using new materials such as fabrics or local earth.
- o Study combustion circulation patterns in buildings to predict pathways of smoke and toxic substances.
- o Study interior air pollution in sealed buildings and develop methods to sustain acceptable interior air quality.

Discussion:

In commercial buildings, most energy is used for lighting and cooling. Increasing the efficiency of lighting could reduce the heating as well as the cooling requirements. Commercial structures will also benefit from materials and controls that more closely and reliably integrate the whole building performance.

Redistribution of Light The lighting provided by solar energy can be excessive at the perimeter of the building while negligible in the interior of the building. Design concepts that collect solar energy in the visible wavelengths and transmit it to the building interior must be combined with automatic controls or artificial lighting to compensate for variations in daylight.

Redistribution of Thermal Energy Energy transfer systems between different locations in a building and the building envelope will facilitate optimum use of solar energy. These systems must provide for energy concentration, that is, concentration of diffuse solar energy falling on a large collection area, distribution of the concentrated energy, and rediffusion of it within the interior space. Concentration must be carried out by techniques that are simpler than the current use of distributed liquid lines; a fluidized bed medium with a high rate of heat transfer is a likely possibility.

Conventional thermal energy distribution by air ducting consumes appreciable electrical energy. Improvement in the cycle efficiency of air-to-air heat pumps in a small structure such as a home is quickly overshadowed by the fan power needed for the distribution system. Replacement of the air duct system with liquid or solid-particle circulation loops requires the development of a simpler means to distribute the thermal energy to the interior space from the circulation loops. This in turn necessitates efficient air heat exchangers and a knowledge of the physics of air circulation, as well as of comfort requirements (see the Intelligent Buildings and Advanced Design Tools section).

Innovative Design with New Materials Opportunities exist to combine innovative building designs with new materials and methods of construction that will yield efficient structures. Examples of these include fabric structures and earth-sheltered structures. Proper direction of these developments and efficient exploitation of promising concepts requires a more fundamental understanding of building thermal performance. New concepts such as flexible insulation for fabric structures must be developed to encourage the application of innovative building design concepts.

Whole-Building Research by Integrating Elements

Recommendation:

- Support proof-of-concept projects to demonstrate the workability of whole-building energy designs.

Discussion:

Buildings are complex assemblages of parts constructed to satisfy the specific needs of the building's owner and users. The building industry contains persons and organizations who address at least seven levels of practical study and analysis, ranging from basic materials to the completed building. These building levels can be classified as follows:

- Materials--wood, aluminum, glass, steel, concrete, plastic, and so forth
- Elements--sized lumber, veneers
- Components--laminated wood doors, doorframes
- Assemblies--doors, frames, hardware, and protective surfaces as a unit
- Subsystems--partitioning including door assemblies, studs, gypboard panels, and protective and decorative surfaces
- Systems--collection of integrated subsystems including wall, partition, structural, ceiling, envelope, and so on
- Whole buildings--specific arrangement and assemblage of building system parts to meet the programmed needs of the building users

Approaches to more efficient use of energy exist at every level of classification as well as at the transition point from one level to the next. For example, the research necessary to convert plastic into an improved weather-protective element can be applied to a wood window frame to form a component. Improved energy performance criteria for envelope or ceiling systems, each of which contain multiple subsystems, are possible in terms of both in-place energy and energy for building operation requirements.

Recent research has explored the fact that systems interact in many ways and that the envelope and ceiling systems must be studied in relation to one another in order to optimize their combined effect on lighting, acoustics, air distribution, and subsequent energy use. It logically follows that the greatest opportunity for efficient use of energy can be studied most effectively at the whole-building level, because at this level the greatest number of building elements (that is, parts) are available for the optimized design of a specific building type.

Proof-of-concept projects are needed to verify the energy conservation concepts in actual buildings. Such projects, if properly and widely communicated to the design professions, would have a highly leveraged effect on the design of new buildings of the same type.

Although numerous whole-building energy conservation concepts have been and can be tested, a specific example is referenced--the "light plenum" concept (Mirkovich, 1983). This concept involves the interrelated action of a ceiling subsystem and an envelope subsystem, which can only be designed as an integrated part of a whole building. Light rays, either direct or diffuse, enter the plenum above the office space from a light shelf over the viewing window at the building's southern exposure. The daylight is reflected throughout the plenum by means of flat reflective surfaces; no curved surfaces or tracking devices are used. This light plenum concept reduces glare and ceiling problems because soft light enters from above, at ceiling level, through diffusing lenses. With the aid of louvers at the side windows and at the plenum, a degree of uniform illumination can be maintained.

INTELLIGENT BUILDINGS AND ADVANCED DESIGN TOOLS

Different areas of a building, such as the perimeter and the interior, may simultaneously require cooling and heating or shading and artificial lighting. The use of sensors and intelligent control systems should permit more efficient energy exchange to meet these disparate needs. Such systems should also be able to deploy the building structure in combination with specific energy storage systems in order to anticipate and smooth out peak demands. Local task illumination and space conditioning limited to occupied areas would reduce overall electric energy requirements as well as peak loads.

New commercial buildings are being designed with integrated communications and data transmissions that can also interface with external networks. One element of this network should be information on the distribution of comfort levels, energy use, and indoor pollution within the building. This should facilitate the optimization of building conditions and energy use that should in turn minimize average energy usage and reduce peak electricity demands.

The intelligent commercial building will include increasing numbers of individual computer work stations. This will approximately double the thermal loads in a typical office space and require different illumination standards for computer display devices.

The discussion of research opportunities related to these and other challenges in buildings is organized as follows:

- Thermochromic and electrochromic coatings
- Operable surface skin ventilation
- Control of mini-environments
- Development of a new generation of sensors
- Improved models of building physics for adaptive control systems
- Advanced building design tools

Thermochromic and Electrochromic Coatings

Recommendation:

- Apply thermochromic and electrochromic coatings to building exteriors for variation of reflectivity.

Discussion:

Meeting variable environmental conditions as well as differing occupancy and use patterns in commercial buildings requires elements with controllable performance characteristics. For example, thermochromic coatings on the building exterior of perimeter areas directly exposed to solar energy would allow the reflectivity and emissivity to vary automatically with temperature levels within the building. Electrochromic films would allow for variation of the reflectivity by the building control system.

Operable Surface Skin Ventilation

Recommendation:

- Develop an improved basic understanding of air flow in multi-storied buildings under different wind loading conditions so that operable surface skins can be readily designed.

Discussion:

Ventilation systems can permit greater energy exchange between exterior and interior building zones. These systems require careful development, since parasitic power requirements for air handlers can sometimes exceed energy savings. Operable building exteriors that admit fresh air can reduce the need for mechanical ventilation and refrigeration systems. A basic understanding of air flow in multistoried buildings with stack effects, multiple subareas, and different wind loading conditions is required before surface skin ventilation systems can be operated to achieve acceptable comfort and air-quality conditions throughout the building.

Control of Mini-Environments

Recommendations:

- Explore methods to control temperature for comfort at the individual's work station.
- Explore methods to control the local environment of computers and other special kinds of equipment.

Discussion:

European building designs such as those in Sweden indicate how proper integration and application of existing technology can lead to much more energy-efficient structures. However, the thermodynamic lower limit for the energy required for personal comfort is well below that which has been achieved. New technology is possible that would provide for and control the comfort of the individual's personal space while allowing less energy for heating or cooling of unoccupied spaces. For example, electromagnetic radiation sources can be used to heat individuals and local subareas with the aid of distributed sensing devices and control systems. Alternatively, infrared reflecting materials can be used on interior building surfaces to create a hohlraum (environment) for thermal radiation. Providing separate, controlled mini-environments for computers, electronic, and other equipment in living or working spaces will allow more flexibility and efficiency in the controlled flow of energy.

Development of a New Generation of Sensors

Recommendations:

- Explore spacial sensors to measure temperature, humidity, air flows, pollution levels, and location of people.
- Perform research on optimal economic locations for sensors.

- Develop sensors for improved control and optimization of the building heating ventilation and air conditioning systems.
- See recommendations in Sensors and Automatic Controls section.

Discussion:

Efficient control of buildings requires a new generation of sensors. These must be capable of measuring conditions directly adjacent to the sensors as well as average conditions and gradients within larger spaces. Measurements of the latter are needed because temperature distributions and pollutant concentration distributions within a building space will change widely, depending on heating or cooling conditions, the occupancy level in the space, the orientation of moveable partitions and doors within the space, and the conditions within adjacent spaces. For example, ceiling diffusers may provide good mixing during periods of cooling, while creating stratified zones during periods of heating. Thus, a few point sensors may give inaccurate indications of the conditions within the space, such as temperature, air flow, and pollution level. Spacial sensors may use incident hemispherical infrared energy to measure the average temperature conditions or average transmission measurements in selected wavelengths to measure average pollution concentration levels. The location and interpretation of such sensors must be closely tied to a better understanding of heat and air transfer within the building. Sensors are also required to measure occupancy levels, pinpoint the location of individuals, measure humidity levels, and detect air circulation patterns and the existence of stagnation regions.

Another class of sensors is needed to monitor the functioning of important elements of a building's heating, ventilating, and air conditioning (HVAC) systems. These sensors should be able to indicate impending failures and clearly alert maintenance and operating personnel to unsafe or erroneous operating conditions, such as malfunctioning outdoor air dampers. This task requires state of the art technology sensors that are simple, rugged, reliable, and inexpensive, not the lightweight or high-precision sensors used for aerospace and other high-technology applications.

Improved Models of Building Physics for Adaptive Control Systems

Recommendations:

- Develop expert systems for use by building maintenance and operational personnel that when integrated with sensors allow maximum comfort with minimum energy use.

Discussion:

Most large and moderate-sized commercial buildings presently use some form of computer control. Newer systems rely on distributed microprocessors with central control of adjustable constraints or control parameters within the microprocessors. However, the program algorithms for these systems are based on oversimplified models of the building physics and do not contain adaptive elements that would allow the controls to use accumulated historic information to forecast peaking requirements or to reoptimize the systems. Along with sophisticated control systems and flexible HVAC systems containing features such as thermal storage, there is the need for proper interface betwen the system and the operator, who may have little if any formal technical training, though substantial hands-on operating experience. The challenge is to provide an expert system that will allow the building to be operated to the occupants' satisfaction by maintenance and operational personnel, without sacrificing the inherent energy-efficient features.

Advanced Building Design Tools

Recommendations:

- Develop graphic input-output modules or computer programs that allow the architect to rapidly analyze the energy consequences of his building design.
- Apply new programming concepts based on advances in the areas of artificial intelligence and expert systems.

Discussion:

Reduction of up to 50 percent of building energy use is possible (Department of Energy, 1984a) if new buildings are designed and existing buildings are modified and operated using currently available information and energy analysis procedures. Loss of energy in building use has persisted in part because of the fragmentation of the building industry, the resulting specialization of the industry members, and the inertia of architects and engineers who are comfortable with the traditional methods of designing and engineering buildings.

Graphic input and output modules for existing computer-aided energy analysis programs are products that can change the way in which energy analysis is included in the design of buildings and can effect new methods of design. These new products must be researched and developed with an understanding of the building industry's existing design methods and procedures.

The processes currently used to design buildings require that the architect synthesize numerous requirements for a specific building during a very short period of time, often only one or two days. Decisions that are made during this time are later refined, but many basic aspects of the building are "frozen" and cannot be economically changed during the building documentation period. Problems in achieving a thorough energy analysis arise because more than 50 percent of all architectural offices in the United States have fewer than six people; these offices are usually unable to afford an energy specialist. The need, therefore, is for a new energy design tool that can be used fast and easily by an architect who is not an energy specialist and by the architect in training. The tool must allow the input of general architectural proposed solutions at this early, yet critical, time in the schematic design process and must be able to display graphically the impact of proposed design alternatives on predicted energy consumption.

Conditions are favorable at the present time for innovation in building design. Many microcomputers are being purchased by small architectural/engineering offices. A number of excellent energy-economic-analysis microcomputer programs already exist and are available for modification (Burt Hill Kosal Rittlemann Associates, 1984; Department of Energy, 1980; Ellenwood, 1985; Lawrence Berkeley Laboratory, 1982; Quadrel and Kroner, 1985; SYRSOL, 1985).

Graphic modules can be added to existing microcomputer energy analysis with user-friendly graphic output modules so that architects can use them routinely. This will require the integration of preliminary energy analysis programs with sketch-pad-type graphic design inputs. The input mode should allow the architect two- and three-dimensional design flexibility. The preliminary energy analysis should be accomplished with a minimum of design inputs (for example, building geographic location, orientation, general construction type, etc.). The software must contain a substantial degree of flexibility and intelligence in order to supply critical design components omitted in the architect's conceptual design, such as default values necessary to provide an energy estimate based on building location, intended function, and type, and past building design decisions made by the user. The program should also be able to internally perform parametric studies and highlight key design parameters that will substantially improve energy efficiency and reduce peak electrical loads (in other words, an internal "what if" procedure). The program must be rapid and flexible enough to repeat this process as additional design details are supplied by the architect. New programming concepts could be applied, based on advances in the field of artificial intelligence.

3

RESEARCH MANAGEMENT STRATEGIES

Now that a series of opportunities for technological innovation has been presented, some research management strategies for the Energy Conversion and Utilization Technologies (ECUT) and Innovative Energy Conservation Concepts (IECC) programs can be offered. These include opportunities at the meta level of innovation, because their successful implementation would help to improve the selection of the most appropriate research or development topics. One strategy is the establishment of a means for regular assessment of the state of technology needs and possibilities, and another is peer review of proposals. Still another is to develop analytical tools for evaluating proposed new processes or products. The overall strategy should emphasize specific useful criteria for project selection, as discussed herein. This chapter also offers comments on how to attract more innovative proposals from competent researchers. Finally, comments are made about the need for interaction between ECUT/IECC and DOE's Basic Energy Science Program, about industry-specific strategies, and about innovation program resources.

USE OF FORUMS AND CRITICAL REVIEW PANELS

One meta-level research management strategy involves the regular assessment of the state of technology and identification of research opportunities for the energy efficiency technology.

The best judges of current needs and the state of a technology are usually the researchers and practitioners in the field, particularly individuals with creative imaginations tempered by healthy and mature skepticism. A continuing relationship based on dialogue between program administrators and expert advisers has very high value for informing administrators of the newest opportunities and of technologies ripe for development. Two modes of action are suggested. One is a regular multidisciplinary forum in which the advisers meet and brainstorm at relatively frequent intervals. Although the agenda would include a review of the most recent technology developments, it primarily would provide an opportunity for a group of exceptionally creative scientists and engineers to conceive new research possibilities. This mode has proved itself already in industrial settings, especially when the participants are properly selected and motivated.

A supplement would be a series of special forums in response to proposals made to the ECUT program or to recommendations by the general panel. The recognition of opportunities, like the invention of new scientific questions, can sometimes move a field ahead faster than finding the answer to a well-recognized problem. Hence, it may be of value to ECUT to also request imaginative or speculative reviews of areas it has already identified as fruitful and where work is currently being pursued (in contrast to conventional critical reviews, which find fault and foreclose opportunities). These specific problem-oriented reviews (with a focus on the diesel engine, for example) may be performed by academic, private sector, and national laboratory experts but, again, will only be as good as the creativity and imagination of the participants.

PEER REVIEW OF PROPOSALS

Although it has its weaknesses and flaws, the procedure of peer review has served as well as any other procedure yet devised to guide the allocation of funding for scientific research supported by organizations such as the National Science Foundation and the National Institutes of Health. Other agencies have relied much less on peer review. Whether the results of peer review are strictly followed or used only for general guidance, the method gives the program administrator a means to obtain expert advice in a systematic way on a variety of topics far wider than any single individual could encompass. At the level of the proposals envisioned in this report, where publication of the results of the work would be a visible outcome, peer review is not complicated by proprietary considerations. However, there is some small concern that reviewers could plagiarize the proposals they read. This is a small hazard to accept in return for the vast source of expertise that the method makes available to the program officer. It would probably help all of ECUT to make extensive, regular use of peer review. Regularity is important so that those who submit proposals can come to expect the reading and refereeing of their proposals by professionals in the field.

NEW ANALYTIC TOOLS FOR ASSESSMENT OF PROPOSED RESEARCH

Improved identification of the highest-leveraged opportunities for new approaches to technological innovation may come from better methods of analyses. Such analysis would help to identify which research proposals might lead to results that would at best yield only marginal improvements or provide no net improvement at all. It is desirable to eliminate such proposals as early as possible in the weeding-out process.

Traditional energy balances and measures of thermodynamic efficiency are generally used to help make such evaluations in the field of energy, but these are sometimes too crude to be realistic. For example, a real thermodynamic process must produce its goods at a useful rate; this constraint generally imposes bounds on efficiency and effectiveness that are considerably lower than those derived from the infinitely slow ideal reversible model, on which traditional thermodynamic limits are based. Extensions that incorporate the constraints of finite time operation have been developed for the assessment of many mechanical systems and are being developed for more general systems such as chemical syntheses (Anderson et al., 1984). Evaluations of this sort may be performed in terms of efficiency, power production, consumption, availability, entropy, and even generation of net revenue. The development of such techniques is currently being pursued by scientists and engineers in the United States, Denmark, Italy, and the Soviet Union but has not yet reached the stage of incorporation into the selection of specific research proposals. The ECUT program can direct some of its support to bringing these methodologies to the level of practice, while recognizing that no methodology will entirely substitute for human intuition and subjective judgment.

CRITERIA FOR PROJECT SELECTION

The criteria relevant to the ECUT program and in particular the IECC program, are worth examining closely. The IECC program is intended to provide small grants to help specific projects--especially those considered as high-risk and high-leverage--to cross a barrier encountered in an early development stage.

Proposals appropriate for support by this program could originate in private firms of any size, in federal laboratories, in universities, or even with private individuals; the actual environment of the work is irrelevant. The scale and character of the proposed research is relevant. In order to fit into the IECC program, the proposed research should show strong entrepreneurial innovation. The IECC program, provides a small amount of funding to support R&D on well-defined projects that would enable the principal investigator to demonstrate sufficient proof of concept or develop a convincing proposal for private or government funders. As presently funded, IECC can only help the grantee make a persuasive case for fuller development.

The IECC program should select projects with enough potential to be attractive to larger-scale investors. For this reason it is important to select high-potential projects, which are not necessarily projects with high probability of success. Many proof of concept claims may result, but the program can only be considered successful if some (perhaps only one) of its projects leads to full development and deployment in the marketplace as a clear improvement in efficient use of energy.

Even if none of the projects are successful at that level and in that sense, there is still a way for the IECC program itself to be successful. If its projects generate new knowledge to influence thinking and action by others, they could ultimately result in significant improvements in energy-efficient technologies. To ensure this kind of second-level success, projects should be chosen that are more substantive than simply clever. IECC should deal with important subjects that will lead to publication in recognized (and refereed) journals and that are far-reaching enough to attract the attention of experts working on other related topics.

The ideal strategy for R&D is to invest up to the point at which expected societal benefits do not exceed those from other public investments. Unfortunately, R&D proposals cannot be accurately assessed before the actual investment. As a consequence, only qualitative and heuristic measures of potential outcomes and benefits can be indicated. At best, the options can be ranked by a crude estimate of investment benefits. Moreover, the cost of a rigorous quantitative assessment of a relatively small proposal to DOE/ECUT may well exceed the funds requested in the proposal. Hence, as a practical matter, a project selection procedure should assume no prior knowledge of probable success and of expected benefits. In this situation, how can ECUT/IECC best make investment decisions on small grants for innovative R&D with high leverage? The following are some practical possibilities, beyond a simple method of investment-benefits ranking:

- Identify projects that are missing links between applied research and product/output development and identify experts with the necessary competence for the projects. Examples of the kinds of questions to ask are: Can the product of hydraulic cement R&D be used to improve building efficiency when normal construction methods are used, and can it reduce building energy use over its lifetime? Can R&D in heat transfer processes result in on-site methods for melting road surfacing materials when filling potholes? The missing links addressed here are transfer of technical information and consideration of the feasibility of that transfer in the context of its potential application. Formal mechanisms to discover such missing links and identify individuals with the technical competence to address them might include forums of experts, advisory panels, contests, demonstrations, fairs, prizes, and various special events sponsored by the media or by universities.

- Emphasize R&D investments that will lead to medium-term consumer payoffs (3-10 years). Omit consideration of investments requiring 10 or more years of further development. The benefits of such long-term projects are worth less than half those of medium-term projects, and long-term projects may well be overtaken by newer and unforeseen technologies before reaching such a far-off horizon.
- Evaluate projects in terms of their ultimate impacts on consumers or industries. Small benefits per individual over large numbers of users are likely to have very large total benefits to the economy. For example, a $100-a-year savings per individual, although less than 2 percent of gross per capita personal income, would save the economy approximately $22 billion per year. Yet technological advances with benefits as diffuse as this are unlikely to attract private investment unless they fall into very special categories, for example, single, simple, and salable devices.
- Ensure that the pool of investment projects being supported by DOE as a whole reflects in the aggregate a risk-neutral philosophy. That is, the program should be neither an exclusive risk taker (selecting only projects with very small probabilities of success but large potential payoffs) nor a risk averter (selecting only projects with large probabilities of success and small potential payoffs). The investment pool should contain both extremes but emphasize projects with moderate possibilities of success and payoff. Preceding discussion implies that the role of IECC tends toward the high-risk, high-payoff end of the spectrum, where a small investment by DOE has the potential for extremely high leverage.

ATTRACTING INNOVATIVE PROPOSALS FROM COMPETENT RESEARCHERS

The scale of support for ECUT/IECC projects is small compared with most academic research projects and tiny compared with most projects in federal or private laboratories (see the Innovation Program Resources section). Given this handicap, to be effective the IECC program must attract particularly creative, imaginative people: They are the ones who will find ways to advance the solution of important problems by innovative means and with only a few thousand dollars. These investigators already have the motivation to do creative work; IECC should provide incentives for them to choose to think about problems and projects that serve IECC's goals and that would otherwise not be supported because of the competition of other problems that might be chosen by investigators. It is important to stress such benefits, because the financial and temporal scales of program support will not of themselves be attractive to the researcher, who basically seeks support for programs with flexible funds over long periods. Benefits that ECUT/IECC can offer include:

- Providing a gateway to researchers in the basic sciences into the world of applied and developmental work, a kind of access that is not easily found by academics outside of engineering schools.
- Helping successful grantees obtain funding and technical support elsewhere, for further project development.
- Helping grantees find experts with specific technical skills or specialized knowledge that would advance their projects.
- Minimizing administrative requirements, red tape, and unnecessary reporting, which act as disincentives, especially for small projects.
- Publishing information about new technologies, methods, and findings that will enhance the technology transfer from successful projects and attract additional innovative proposals; perhaps 10 percent of program funds can be used in this way.

INTERACTION WITH THE BASIC ENERGY SCIENCES PROGRAM

One opportunity relates directly to the improvement of the innovation program's overall effectiveness. The Committee strongly recommends that ECUT/IECC make a deliberate, extensive effort to establish closer and much more frequent interaction with DOE's Basic Energy Sciences Program, particularly the Engineering Research Program. Such interaction would help to improve the flow of ideas, technologies, and scientific results from the basic level to the applications and developmental levels. It is not important who takes the initiative to establish and maintain this interaction; it is very important that someone does. Such interaction should enhance all of the aforementioned strategies for research management.

INDUSTRY-SPECIFIC STRATEGIES

There are strategies that are specific to particular industries associated with the seven technical areas about which recommendations are made in this report. For example, some of the materials-processing industries are perhaps at the stage where the U.S. steel industry was several years ago, when industries of other nations were able to invest in R&D for new technology while their U.S. counterparts continued to produce steel with old and outdated equipment. Only by identifying and pursuing opportunities for more efficient use of resources can the U.S. materials-processing industry remain competitive with those of other nations. This can be seen in the way the U.S. cement industry neglected the development of the U.S-invented macro-defect-free cements, which the British have vigorously adopted.

Although strategies to address the basic R&D investment problems of various industries are beyond the scope of DOE's operations, it is helpful to maintain an awareness of the larger context for technical innovation in industry, of which energy is but one component. For example, many-high technology industries experiment with novel and innovative ways to generate and profit from innovative ideas (Rosenfeld, 1983). DOE may wish to search out such innovation programs in the private sector and evaluate their application to DOE's own R&D strategies. It is also important to state that the fundamental problem is not DOE's choice of R&D topics, but its lack of long-range commitment to fund what it takes to turn R&D-derived new knowledge into commercially viable products or processes.

INNOVATION PROGRAM RESOURCES

In conducting this study, the Committee was briefed by the program manager of the IECC program, who presented a summary of program characteristics and a comparison of three DOE programs that target a community of individual entrepreneurial inventors (rather than established energy research centers) (see Tables 3-1 and 3-2). The purpose of the briefing was to help the Committee understand the special role of the IECC within the larger framework of ECUT and other DOE programs.

The IECC program has a small annual budget and seeks to distribute grants on the order of $15,000 each (see Table 3-3). Thus, many of the recommendations made in this report are clearly beyond the capability of IECC to implement. However, they are generally applicable to ECUT and, selectively, to other programs in the Office of Conservation.

With this in mind, the Committee recognizes that IECC and the Energy Related Inventions Program (ERIP) with which it is now grouped (as part of a recent reorganization) have a special role to play. Within a major organizational framework committed to inherently innovative R&D, IECC seeks to elicit and support projects that are particularly innovative and is directed toward entrepreneurial inventors who are not otherwise likely to obtain funds to pursue their ideas.

The Committee agrees with the need for the IECC program and believes it can make valuable contributions. The many recommendations given in this report are directed toward that end. However, the Committee has serious reservations: There is concern that IECC is simply too small and limited in flexibility to benefit from the recommendations and adequately achieve its intended purposes.

For IECC to pursue many of the research directions the Committee has identified, it needs access to laboratory facilities and equipment. Most of the competent research workers are likely to be affiliated with such laboratories in universities or with private firms. As a practical matter, these persons usually seek funds sufficient to cover the overhead expenses of established facilities and to pay salaries for a significant period of time. A grant of $15,000 will pay for approximately 50 days of a researcher's time, not counting purchase of equipment and materials. This seems to limit the grants to work that fits

TABLE 3-1 Characteristics of the Innovative Energy Conversion Concepts Program Within The Department of Energy's Energy Conversion and Utilization Technologies Program

Objectives

- To seek innovative concepts[a] for alternative fuel use or improved energy efficiency in conversion storage and end use
- To investigate technical feasibility, become temporary sponsors for innovative concepts, and accomplish technology transfer

Recent accomplishments

- Solicited proposals on innovative building materials and funded 12 research proposals; concepts from small businesses, universities, and research organizations were funded for about $15,000 each

Selected activities of fiscal year 1984

- Hold meeting to transfer innovative building materials concepts to Department of Energy buildings program and private researchers for further development
- Conduct analysis of potential research opportunities in energy conversion to structure a solicitation for novel energy conversion concepts
- Conduct analysis of energy conservation potential of innovative uses of electromagnetic radiation (microwaves, for example)

[a]Novel approaches fundamentally different from current practices, rather than "basic research or incremental optimization" outlined in the fiscal year 1983 annual operating plan.

SOURCE: Terry M. Levinson, Department of Energy.

TABLE 3-2 Comparison of Three DOE Programs that Appear to Be Similar but Are Not

Program	Approach	Number and Size of Awards in FY 1983	Potential Sponsors	Phases	Source of Proposals	Advisors/ Reviewers
CE/ECUT	Actively solicits new ideas for energy conservation using RFPs	12 awards of of approximately $15,000 each	Conservation & renewable energy offices and private sector	No phases; only seed money before being trans-ferred	Small businesses colleges universities, research institutes	National Academy of Sciences
Energy Research/ SBIR	Actively solicits new ideas for all of DOE in 25 years research areas, of which only Materials may pertain to conservation; a few pertain to renewables	106 Phase I awards ranging from $35,000 to $50,000 each	DOE and private sector	Phases 1 and 2 funded by Energy Research program; Phase 3 to be done by private sector	Small businesses only	DOE
CE/ERIP	Passively funds unsolicited ideas for all of DOE	Varies; sizes of awards up to $100,000	DOE and private sector	No phases	Inventors	National Bureau of Standards

NOTE: CE = Conservation Energy; ECUT = Energy Conversion and Utilization Technologies; SBIR = Small Business Innovation; ERIP = Energy Related Inventions Program.

SOURCE: Terry M. Levinson, Department of Energy.

into a larger program that already has facilities and support or to the development of concept papers and proposals for more funding. It does not preclude worthwhile outcomes, and grants of this size do attract interested and qualified applicants. However, the recommendations of the Committee could be implemented only by an organization with considerably more flexibile grant size. Perhaps such flexibility will result from the recent reorganization under which IECC and ERIP will be more closely linked.

The corresponding concern of the Committee relates to the overall IECC budget. Implementation of the recommendations for research management strategies alone does not appear possible within current staff constraints. There is a realistic critical mass of grants necessary to justify a level of program staff activity in managing the program as recommended. These recommendations applied to ECUT as a whole appear more realistic in scale but not wholly appropriate in function; perhaps the combined IECC/ERIP program will provide the critical mass of grants to justify the more rigorous management approach advocated by the Committee. Whatever the case, the Committee concludes with a final recommendation: determine what the minimum level of grants should be to justify an investment in the quality of management needed to make the program successful. If this can be done through some combination of programs and/or additional funds, the Committee believes that further pursuit of the IECC program would be greatly enhanced.

TABLE 3-3 Energy Conversion and Utilization Technologies Program Budgets for FiscalYears 1981-1985, in millions of dollars

	Fiscal Year				
Budget Areas	1981	1982	1983	1984	1985
Combustion and thermal sciences	5.840	4.00	4.4,000	4.864	5.500
Materials sciences	1.669	2.428	2.775	1.983	4.832
Catalysts/biocatalysis	0.491	0.849	0.525	0.800	2.000
Tribology	0.0	0.0	1.000	1.153	2.700
Innovation (IECC)	0.0	0.0	0.300	0.200	.575
Program direction	0.200	0.182	0.230	0.277	.293
Capital equipment	0.0	0.384	0.0	0.0	1.666
Total	8.200	7.843	9.230	9.277	17.566

NOTE: IECC = Innovative Energy Conversion Concepts program.

SOURCE: Terry M. Levinson, Department of Energy.

4

THE IMPLICATIONS AND RECOMMENDATIONS

OVERVIEW

This chapter briefly reviews the rationale for energy conservation and then presents the recommendations of the Committee. The chapter closes with suggestions of how the Department of Energy (DOE) and the Energy Conversion and Utilization Technologies (ECUT) program can pursue more innovative research and development (R&D) programs.

The motivation for energy conservation in 1973 was the United States's response to a crisis of scarcity--not a shortage, but a very sudden increase in price and reduced availability of fuels in some regions. There was considerable skepticism among people in the energy supply business and in U.S. regulatory agencies regarding the magnitude of the elasticities of demand for energy: They believed that demand would remain high even as prices increased rapidly. Others, however, such as those close to vulnerable energy-intensive industries and certain economists specializing in energy analysis at consulting firms and academic centers, regarded increased efficiency of energy use and the corresponding reduction of demand for fuel as vital, logical responses that would play an important role in the panoply of responses to the "oil crisis." The energy users turned out to be correct; they were able to reduce their demand in a variety of ways, from short-term housekeeping improvements to long-term, sometimes slow changes of capital equipment, and therefore U.S. energy consumption fell off markedly in the 1973-1983 decade.

The question remains: Should there be a federal role in the stimulation or advancement of energy efficiency, at a time when demand has fallen so far and when supplies have continued to be so available that one hears about oil gluts, and not at all about oil scarcities? However large these surpluses seem now, fossil and nuclear fuels are ultimately nonrenewable resources (Darmstadter et al., 1983). The cheapest, most readily available resources of oil, gas, coal, and uranium are steadily drawing down. It is unlikely that we will confront sharp, total Malthusian (resource exhaustion) scarcities, but steadily growing Ricardian (price increase) scarcities forced by increasingly costly methods for winning fuels from the environment are inevitable. If the analysis developed by Hubbert (1969) is valid, these scarcities are even predictable.

Optimistic economists emphasize our general technological capability to find substitutes in response to price signals; pessimistic geologists and other scientists emphasize the need for advanced R&D to explicitly develop those technological capabilities. The economist can afford to be optimistic because the process of finding technical solutions to Ricardian scarcities is assumed to occur naturally in response to economic developments. The scientist stresses pessimism because it focuses attention on the need for investment in R&D if the economist's technology assumptions are to be realized.

In adapting to the long-term growth in the cost of a depletable--and depleting--resource, the private sector will not, on its own, develop the needed technologies. A federal role is necessary.

In addressing the question, the Committee sees two strategies: (1) insurance, in which a government role is necessary and not simply accessory, and (2) economic efficiency, in which the government augments the private sector.

- The Insurance Strategy. Conduct research on and develop technologies that can be kept in reserve and called into use in the event of sudden scarcities or unforeseen crises.
- The Efficiency Strategy: Enhance the public good by supporting research on increased efficiency of energy use and other resources wherever the public benefits are large but too diffuse to be captured by private investors.

These two strategies, although entirely compatible, have somewhat different implications.

The Insurance Strategy

The insurance strategy requires analysis of contingencies so that responses can be identified and research designed for technologies that, if successful, will remain in reserve until they are economically viable as fuel prices increase or as some crisis occurs.

The specific projects to be supported can be selected from the spectrum of opportunities on the basis of estimates of probable success, maximum possible impact (easier to estimate than probable impact if successful), probable time either to success or discard, and cost of maintaining reserve.

The Efficiency Strategy

The strategy of efficiency calls for maintenance of a portfolio of R&D projects that are designed to provide economically competitive technologies at the time of their completion. The portfolio viewpoint virtually demands maintaining a research program with enough breadth to encompass (1) long-term, high-risk, and high-potential projects, (2) a middle group of strong projects in the main lines of progress, and (3) projects that sustain the rest of the R&D enterprise by supplying the stream of reliable data required to carry out innovative work. The high-risk portion is like venture capital investment, the data-supplying portion is analogous to municipal and government bonds; and the rest is like the bulk of an investment portfolio designed to give both growth and income, with a balance of moderate risk and security. The one additional criterion that distinguishes what should be publicly supported is the diffuseness and public character of the benefits, that is, the inability of the private investor to capture the benefits of a socially worthwhile technology investment. An important motivation for public support is to spread the risk so that no single investor is overexposed.

RECOMMENDED TECHNICAL AREAS OF RESEARCH

With the assistance of inputs from other experts at its workshop, the Committee examined a wide field of technical areas and evaluated ongoing R&D, the potential and opportunities for significant improvements in energy efficiency as evidenced by current frontier technology, and specific examples that illustrate the opportunities. With the goal of providing specific advice on the areas of highest opportunity, seven broad areas of scientific and engineering research were selected as particularly interesting. Some of these offer research projects that are still in early stages of development and that could repay relatively small investments with large increases in energy efficiency if successful.

The seven research areas are:

- Heat transfer
- Heat engines and cycles
- Sensors and automatic controls
- Materials processing
- Special materials
- Building envelopes
- Intelligent buildings and advanced design tools

Within these areas specific research and development projects are recommended not for funding but only as worthy of further attention. The actual funding decisions should be made on the basis of what is said in each proposal.

Table 4-1 lists the seven research areas worthy of interest and summarizes how such research contributes to energy savings or efficiency. Table 4-2 lists the Committee's specific recommendations.

RECOMMENDATIONS ON ECUT/IECC RESEARCH MANAGEMENT STRATEGY

The Committee considers the judicious choice of topics important and recommends the development or improvement of tools for identifying and evaluating topics and proposals.

The following strategic approaches are recommended:

- Use of forums and critical review panels to tap the pool of experts working on advanced scientific research that has application to energy efficiency in order to identify useful research areas;
- Use of peer review, drawing upon the same pool of experts, to evaluate specific proposals;
- Development of new analytical tools for planning of research based on models that incorporate thermodynamic concepts;
- Application of several practical criteria to the current project selection process, taking into account such factors as addressing missing links between research and markets, time to payoff, spread of benefits, and balancing the risks of the project portfolio;
- Addressing the problem of how to attract the more competent innovative researchers to a program based on small grants;
- Establishment of a way to interact more with DOE's Basic Energy Sciences Program in order to improve the flow of ideas and scientific results and to enhance overall effectiveness.

By using a small part of the total budget for these activities, the net effectiveness of the innovation program could be expected to improve over a period of 2-4 years.

The Committee feels that the Innovative Energy Conservation Concepts Program as currently structured and funded is not in a position to effectively implement the technical and management recommendations offered in this report. Therefore, it is recommended that DOE increase the staff and funding levels to permit a more effective program.

TABLE 4-1 Research Areas and Their Potential Contribution to Energy Savings

Research Area	Contribution to Energy Savings
Heat transfer	In general, heat losses can be reduced, increasing available work in engines or useful process heat
Equipment needs	Improved heat exchange equipment will increase engine efficiency and permit the practical development of innovative higher-efficiency energy conversion systems
Working fluids	New working fluids are needed to convert low-grade waste heat to useful work
Resistant materials and insulation	As materials in machines, furnaces, and boilers degrade, useful heat is lost; improved materials will result in direct energy savings
Component replacement	When components such as radiators degrade, energy is wasted; the availability of cheap, easy-to-replace components will result in direct energy savings

TABLE 4-1 Research Areas and Their Potential Contribution to Energy Savings (continued)

Research Area	Contribution to Energy Savings
Heat engines and cycles	Generators and compressors will produce more work for the same energy input
Augmentation of heat transfer	By augmenting heat exchange on the air side of an air conditioning cycle, efficiency can be significantly improved; augmented heat exchange will also allow improved recovery of work from the waste heat of industrial energy machinery
Reduction of heat transfer	Within an engine, heat flow through the combustion chamber reduces useful work; by reducing heat transfer, efficiency can be increased
Reduction of thermal distortion and friction	Uneven heating of moving parts causes uneven expansion, greatly increasing friction; by understanding and controlling temperature distributions with the combustion chamber and piston, efficiency can be increased significantly

TABLE 4-1 Research Areas and Their Potential Contribution to Energy Savings (continued)

Research Area	Contribution to Energy Savings
Heat engines and cycles (continued)	
Improvement of combustion characteristics	Within the diesel engine the temperature of combustion varies within the cycle; by modifying the cycle to minimize the lower temperature portion, efficiency can be improved. Other improvements to engines permit use of alternative fuels that may be cheaper
Improvement of path of piston	Theoretically it is possible to extract 10-15 percent more work from a unit of fuel if the time path of the piston can be adequately controlled
Improvement of control within the cycle	Air conditioners and combustion engines can experience improved efficiency if the movement of their expansion valves and cylinders, respectively could be more precisely controlled
Improved materials to resist higher temperatures	Higher temperature engines will operate at higher efficiencies

TABLE 4-1 Research Areas and Their Potential Contribution to Energy Savings (continued)

Research Area	Contribution to Energy Savings
Sensors and automatic controls	These have application to improved performance of heat engines and cycles and to virtually any combustion and heat exchange process
Improved sensor technology	Many processes that take place at high temperatures or in corrosive environments can be made to experience improved efficiency if measurements of temperature, pressure, and flow rate could be accurately obtained
Models to extend the scope of sensors	Computer models make it possible to infer the temperature, pressure, or flow rates in many environments from indirect sensor measurements; the effect is to increase energy efficiency through improved process control
Models in the process loop	Improved control of a very wide variety of energy and industrial processes will increase energy efficiency; models that are integrated with the process provide such control

TABLE 4-1 Research Areas and Their Potential Contribution to Energy Savings (continued)

Research Area	Contribution to Energy Savings
Sensors and automatic controls (continued)	
Artificial intelligence, expert systems, robotics	These represent further advances in using advanced computer technology and feedback control to improve energy efficiency through more precise control of any industrial process
Remote sensing/novel applications	Remote sensing technologies such as computer-aided tomography, nuclear magnetic resonance, ultrasonics, laser beams, and advanced optical systems allow for the detection of temperature, pressure, stress, and deformation without influencing the behavior of the systems measured; this capability greatly enhances the ability to control many processes and thereby increases energy efficiency

TABLE 4-1 Research Areas and Their Potential Contribution to Energy Savings (continued)

Research Area	Contribution to Energy Savings
Materials processing	Major amounts of energy that are used in processing materials from ores can be reduced; in addition, many new materials can be produced that will improve the energy efficiency of machinery, heat exchangers, and industrial processes
Innovation in traditional materials processing	Metals can be extracted from ores at great reductions in energy consumption
High-temperature processing	Many industrial processes involving chemical reactions use less energy when carried out at higher temperatures
Surface modification treatments	Advanced technologies can alter the surface of materials to achieve improved wear, reduced friction, and better heat exchange properties, all of which have the effect of improving energy efficiency in many processes

TABLE 4-1 Research Areas and Their Potential Contribution to Energy Savings (continued)

Research Area	Contribution to Energy Savings
Materials processing (continued)	
Rapid solidification processing	Many important industrial materials, such as thin filaments and ribbons, can be produced with these methods at greater energy efficiency than with other methods; in addition, as precision-made thin materials replace heavier materials in many applications, energy embodied in the materials production process is reduced
Chemical synthesis	As above, the result is lower energy in manufacture, as well as new products, which in turn reduces energy consumption in many processes
Shaping of ceramics	Ceramic combustion engines and heat exchangers can accept higher temperatures of operation, thereby increasing the efficiency of the respective processes; the ability to create the correct shapes is critical to proper functioning

TABLE 4-1 Research Areas and Their Potential Contribution to Energy Savings (continued)

Research Area	Contribution to Energy Savings
Materials processing (continued)	
Forest products industry application	There are many innovative ways to reduce the energy used in producing wood and paper products, using some of the aforementioned innovations as well as other methods
Special materials	These materials can reduce the use of energy in many construction and industrial applications
Macro-defect-free hydraulic cements	By reducing the time between replacements (such as of pavement) and other infrastructure, these cements can conserve significant amounts of energy
High-performance ceramics	In addition to operating at higher temperatures, thereby reducing the energy consumed by improved internal combustion engines, these ceramics can replace more energy-intensive metals in many structural and mechanical applications

TABLE 4-1 Research Areas and Their Potential Contribution to Energy Savings (continued)

Research Area	Contribution to Energy Savings
Special materials (continued)	
Advanced alloys	Energy is conserved by using materials that allow for higher engine operating temperatures, particularly in aircraft; additional energy savings are associated with lighter materials in aircraft or building structures
Superconducting devices	Major reductions of energy loss are theoretically achievable with superconducting motors, generators, and transmission lines
Shape-memory alloys	These alloys can be used to make low-temperature energy conversion devices, allowing for the capture of large amounts of waste heat in industry and buildings
Application of special materials to buildings	These materials can conserve energy by displacing more energy-intensive materials, reducing heat losses, and capturing waste heat

TABLE 4-1 Research Areas and Their Potential Contribution to Energy Savings (continued)

Research Area	Contribution to Energy Savings
Special materials (continued)	
Application of special materials to infrastructure	Macro-defect-free cements and other materials offer the opportunity to reduce time between repairs of road surfaces, drainage structures, and water and sewer pipes, thereby reducing the energy used in construction
Building envelopes	Buildings breathe through their envelopes (walls and ceilings), thereby exchanging energy with the external environment; research in this area can greatly increase the energy efficiency of buildings
Residential structures	Research should be on insulation of surfaces and improved windows to minimize adverse heat exchanges
Commercial structures	Research should be on redistribution of thermal energy and of light within the building in order to match local intensity of energy use with the actual need

TABLE 4-1 Research Areas and Their Potential Contribution to Energy Savings (continued)

Research Area	Contribution to Energy Savings
Building envelopes (continued)	
Whole building research by integrating elements	This research would explore a very wide range of architectural innovation, resulting in more energy-efficient building design for wide application
Intelligent buildings and advanced design tools	The use of advanced sensors and controls, monitored by dedicated computers, can optimize the utilization of energy
Thermochromic and electrochromic coatings	By controlling reflectivity, solar incident energy can be absorbed or reflected as needed, reducing air conditioning and heating needs
Operable skin surface ventilation	By controlling air exchanges between the building and the environment, air conditioning and heating needs can be reduced

TABLE 4-1 Research Areas and Their Potential Contribution to Energy Savings (continued)

Research Area	Contribution to Energy Savings
Intelligent buildings and advanced design tools (continued)	
Control of mini-environments	By maintaining human comfort levels or equipment-required temperatures only in the small spaces where needed, air conditioner and heater energy expenditures can be reduced
Development of a new generation of sensors	By sensing temperature and humidity within and outside of buildings, precision comfort control at lower energy expenditure can be achieved
Improved models of building physics for adaptive control systems	By predicting temperature and humidity with greater precision, equipment can be regulated and air flows controlled to provide comfort levels with minimum use of energy
Advanced building design tools	Using state-of-the-art computers, architects can simulate the energy implications of various design concepts very quickly and early in the design process

TABLE 4-2 Specific Topics Recommended for Innovative Research in the Seven General Research Areas

Research Area	Specific Recommendation
Heat transfer	
Equipment needs	• Conduct research on some of the detailed mechanisms for heat transfer, such as heat transfer in turbulent flows, innovative heat exchanger designs and materials, mass trasnfer through porous materials, and on radiation heat transfer involving gray fluids in complex geometries
	• Develop improved heat exchangers (applications to kraft pulp mills have one quad potential)
	• Explore electrochemical high temperature heat as applied to electric conversion devices
Working fluids	• Search for fluids that will not attack surfaces at high operating temperatures
Resistant materials	• Explore use of oxide films to coat materials to resist oxidative attack
	• Solve the problems of ceramic heat exchangers
	• Develop improved methods for joining nonductile materials
	• Improve the understanding of soil as an insulation and heat storage medium and as it is influenced by moisture migration

TABLE 4-2 Specific Topics Recommended for Innovative Research in the Seven General Research Areas (continued)

Research Area	Specific Recommendation
Resistant Materials (continued)	
	• See recommendations for Special Materials area
Component replacement	• Develop cheap materials that degrade gracefully in heat exchangers
Heat engines and cycles	
Augmentation or reduction of heat transfer	• Improve heat exchange within the regenerator of Stirling and Ericsson engines
	• Augment air-side heat transfer in air conditioners and compressors by exploring new surface geometries, lower fluid velocities, and use of new materials
	• Augment gas-side heat transfer in high temperature heat exchangers of bottoming cycles by using shallow fluidized beds
	• Improve cooling techniques for turbine air foils and use of ceramic materials to achieve higher power densities
	• Develop lightweight heat exchangers for bottoming cycles used with diesel or gas turbine engines
	• Seek to reduce turbulence and to approach laminar flow within the cylinder
	• Pursue additional research on the fluid dynamics within the cylinder, to extract more work from the heat produced

TABLE 4-2 Specific Topics Recommended for Innovative Research in the Seven General Research Areas (continued)

Research Area	Specific Recommendation
Reduction of thermal distortion and friction	• Study convective heat transfer in reciprocating engine cylinders
	• Study the relationships among flame propagation, fluid dynamics, convective heat transfer, and solid conduction
Improvement of combustion characteristics	• Study the process of mixing and combustion of diesel fuel
	• Seek to speed up the slow diesel burning process at the end of the combustion stroke
	• Experiment with stratified charge ignition engines to approach diesel performance and provide multifuel use
Improvement of path of piston	• Develop a motion transducer that can be introduced between the piston and flywheel in an Otto or diesel engine
Improvement of control within cycle	• Explore variable capacity compressors
	• Develop improved expansion valves
Improved materials to resist higher temperatures	• Develop high-temperature, high-strength, and and machinable ceramics
	• See recommendations for Special Materials area

TABLE 4-2 Specific Topics Recommended for Innovative Research in the Seven General Research Areas (continued)

Research Area	Specific Recommendation
Sensors and automatic controls	
Improved sensor technology	• Develop sensors that can function in more stressful environments such as high temperatures, high-speed moving parts, radiation, and chemical reactive environments
Models to extend scope of sensors	• Expand research of basic physical processes so that models can be designed for a very wide variety of situations not accessible to sensory devices
Models in the process loop	• Focus research on nuclear reactors, combustion engines, metal-working equipment, and ceramic formers
	• Study the process of wear on surfaces, reliability of components, and brittleness of metals by using more advanced sensory tools
Artificial intelligence, expert systems, robotics	• Conduct research integrating all steps in the standard control loop from sensing through processing to control signal and feedback
Novel application of sensors	• Experiment with computer-aided tomography in a variety of applications such as neutron radiography in metal forming; differential thermometry; laser refraction, diffraction and scattering for inspection of close tolerances; on-line potentiometry for tracer ion concentration; and description of turbulent eddyies within a fluid

TABLE 4-2 Specific Topics Recommended for Innovative Research in the Seven General Research Areas (continued)

Research Area	Specific Recommendation
Novel applications of sensors (continued)	
	• See recommendations in Building Envelopes area
Materials processing	
Innovation in traditional materials processing	• Search for opportunities in mining, extraction, and refining and forming of metals
	• Explore extraction of metals from powdered ores
	• Explore methods for near net shape fabrication
	• Explore improved instrumentation, controls, and robotic systems
High temperature processes	• Experiment with chemical reactions at higher temperatures to exploit increased energy efficiency
	• Explore metal extraction from powdered ores
	• Seek greater thermodynamic efficiency in heat engines
Surface modification treatments	• Explore chemical vapor deposition for coating of heat exchangers, pipe, reactor vessels, and so forth for critically stressed materials
	• Explore laser surface alloying at low-energy input combined with glazing as a way of surface modification
	• Explore ion beam implantation to increase the range of economic application for small critical components in high-wear situations

TABLE 4-2 Specific Topics Recommended for Innovative Research in the Seven General Research Areas (continued)

Research Area	Specific Recommendation
Materials Processing (continued)	
	• Explore molecular beam deposition for tailoring the microstructure of composite materials
	• Study the basic physical/chemical processes in all the aforementioned approaches
Chemical synthesis	• Conduct research to address critical fundamental issues related to the design and synthesis of molecular precursors
	• Conduct research on optimal reaction phase decomposition pathways leading to the final consolidated net-shape product
Shaping of ceramics	• Explore photolithographic techniques coupled with dry etching
	• Construct wafers by laser chemical vapor deposition
	• Explore microwave heating for the diffusion bonding step
Forest products industry applications	• Seek to apply any of the aforementioned innovations to energy-intensive materials industries, such as forest products

TABLE 4-2 Specific Topics Recommended for Innovative Research in the Seven General Research Areas (continued)

Research Area	Specific Recommendation
Special materials	
Macro-defect-free hydraulic cements	• Conduct research to determine the structure-property relationship
	• Conduct research to define the nature of interactions between polymer additives and cement matrix
	• Explore applications using various materials, such as nylon, iron, powder, and organic fibers, to produce special properties such as high-impact resistance and screening of electromagnetic radiation
High performance ceramics	• Explore use of computer-aided tomography to achieve better control of material shape
	• Explore use of transformation toughening agents to strengthen the ceramic body
	• Produce ceramic powders by laser or radio-frequency plasma pyrolysis of molecular precursors to produce low-porosity ceramics
	• Explore incorporation of strong fibers into the ceramic body to inhibit cracking
	• In order to develop better understanding of the fundamental processes described above, perform optimization and scale-up studies

TABLE 4-2 Specific Topics Recommended for Innovative Research in the Seven General Research Areas (continued)

Research Area	Specific Recommendation
Special materials (continued)	
	• Continue evaluation and testing of advanced materials in gas turbine and diesel engines
	• Perform research on composite manufacture, aimed at reducing synthesis to a continuous-flow, chemical-engineering-type process in order to reduce manufacturing costs
Advanced alloys	• Seek a potentially new class of superalloys through controlled thermal decomposition of homogeneous supersaturated alloys to create complex three-phase superalloy composites
	• Seek to replace titanium alloys with high-specific-strength aluminum alloys and composite materials for cooler compressors and fan sections of engines
	• Explore rapid solidification of titanium-base alloys to obtain desired particle-strengthened structure
	• Explore the synthesis of inert particle dispersion-strengthened alloys by reaction processing for titanium alloys (this can be coupled with a broader spray-deposition initiative)
Superconducting devices	• Seek to develop materials with properties superior to niobium titanium
	• Explore specific applications, for example, the next-generation high-energy accelerator; advanced high-field, high-uniformity magnets; and transport by magnetic levitation

TABLE 4-2 Specific Topics Recommended for Innovative Research in the Seven General Research Areas (continued)

Research Area	Specific Recommendation
Special materials (continued)	
	• Seek to develop a stable ductile material that becomes a superconductor above the boiling point of hydrogen
	• Explore the application of new materials such as thin-film niobium nitride and several organic superconductors
Shape-memory alloys	• Develop new shape-memory alloys with higher transformation temperatures for application to more efficient energy conversion devices
Application of special materials to building construction	• Research improvement of wood properties
	• Apply computer-aided-design and computer-assisted manufacturer techniques to the lumber industry
	• Apply macro-defect-free cements to the construction industry
	• See recommendations in Building Envelopes area
Application of special materials to infrastructure	• Develop advanced procedures for repairing roads by using on-site melting and reforming
	• Develop the use of additives such as fiberglass to improve durability of roads
	• Study and develop cements and improved asphalts
	• Develop coating and relining techniques for conduits and tunnels using catalytically induced polymerization of fluid additives

TABLE 4-2 Specific Topics Recommended for Innovative Research in the Seven General Research Areas (continued)

Research Area	Specific Recommendation
Building envelopes	
Residential structures	• Develop composite materials such as oriented strand board, stressed skin structures with foam cores, and fiber-reinforced materials
	• Conduct research on material properties of building envelopes in the presence of hazards such as fire, flood, and earthquake
	• Develop commercial window materials with properties such as infrared reflectivity and improved resistance to heat transfer; explore the use of sealed window gaps using low-conductivity gases or vacuums
	• Explore new insulation concepts, such as microfine powders for use in appliances
	• Develop inexpensive and effective interior wall insulation panels
Commercial structures	• Develop new design concepts to improve the distribution of solar-source lighting within a building
	• Develop energy transfer systems to redistribute heat within a building for optimal interior temperature control
	• Study combustion circulation patterns in buildings to predict pathways of smoke and toxic substances

TABLE 4-2 Specific Topics Recommended for Innovative Research in the Seven General Research Areas (continued)

Research Area	Specific Recommendation
Building envelopes (continued)	
	• Study interior air pollution in sealed buildings, and develop methods to sustain acceptable interior air quality
Whole building research by integrating elements	• Support proof-of-concept projects to demonstrate the workability of whole building energy designs
Intelligent buildings and advanced design tools	
Thermochromic and electrochromic coatings	• Apply to building exteriors for variation of reflectivity
Operable surface skin ventilation	• Develop an improved basic understanding of air flow in multistoried buildings under different wind loading conditions so that operable surface skins can be reliably designed
Control of mini-environments	• Explore methods to control temperature for comfort at the individual's work station
	• Explore methods to control the local environment of computers and other special kinds of equipment
Development of a new generation of sensors	• Explore spacial sensors to measure temperature, humidity, air flows, pollution levels, and location of people

TABLE 4-2 Specific Topics Recommended for Innovative Research in the Seven General Research Areas (continued)

Research Area	Specific Recommendation
Intelligent buildings and advanced design tools (continued)	
	• Perform research on optimal economic locations for sensors for improved control and optimization of the building heating, ventilation, and air conditioning systems
	• See recommendations in Sensors and Automatic Controls area
Improved models of building systems for adaptive control systems	• Develop expert systems for use by building maintenance and operational personnel that when integrated with sensors allow maximum comfort with minimum energy use
Advanced building design tools	• Develop graphic input-output modules or computer programs that allow the architect to rapidly analyze the energy consequences of his building design
	• Apply new programming concepts based on advances in the areas of artificial intelligence and expert systems

BIBLIOGRAPHY

Ames, K. 1984. Hydraulic circuit design for micro-processors controls on injection molding machines. Pp. 792-794 in the Proceedings of the 42nd Technical Conference and Exhibition, Society of Plastics Engineers, New Orleans, April 30-May 3, 1984. Brookfield Center, Conn: Society of Plastics Engineers.

Anderson, B., P. Salamon, and R. S. Berry. 1984. Thermodynamics in finite time. Physics Today 37(9):62-70.

Argonne National Laboratory. 1983. Energy and Environmental Systems Division 1968 to 1983 Publications. Argonne, Ill.: Argonne National Laboratory.

Battelle Pacific Northwest Laboratories. 1980. An Analysis of the Results of Federal Incentives Used to Stimulate Energy Production. Washington, D.C.: Department of Energy.

Battelle Pacific Northwest Laboratories. 1981. An Overview of Energy Research Opportunities. Prepared for Department of Energy, Energy Conversion and Utilization Technologies Program. PNL-3944/UC-95. Richland, Wash.: Battelle Pacific Northwest Laboratories. December.

Battelle Pacific Northwest Laboratories. 1982. Identification of Energy Conservation Research Opportunities: A Review and Synthesis of the Literature. PNL-3966/UC-95. Richland, Wash.: Battelle Pacific Northwest Laboratories. March.

Benson, D. K. 1983. Solid State Phase Change Materials. Energy Technology 10. Washington, D.C.: Government Institutes. Inc. June.

Berg, C. A. 1973a. Conservation via Effective Use of Energy at the Point of Consumption. Washington, D.C.: Institute for Applied Technology, National Bureau of Standards. April.

Berg, C. A. 1973b. Energy Conservation Through Effective Utilization. Washington, D.C.: Institute for Applied Technology, National Bureau of Standards. April.

Bertram, K. M., C. L. Saricks, and E. W. Gregory II. 1984. Using An Industry Coordination Meeting in the Development of Summary Information on Truck Energy Efficiency Measures. Argonne, Ill.: Argonne National Laboratory.

Boot, A. H., and F. G. H. van Wees. 1983. Temperatures of Industrial Process Heat. Petten, Netherlands: Bureau Energie Onderzoek Projekten.

Brown, L. A. 1981. Innovation Diffusion. London: Methuen.

Burke, J. 1979. Connections. Boston, Mass.: Little, Brown.

Burt Hill Kosar Rittlemann Associates. 1984. Energy Economics of Design Options (Version of CIRA). Proprietary software package. Butler, Pa. Burt Hill Kosar Rittleman Associates.

Cardinal Management Association, and Department of Energy, Assistant Secretary for Conservation and Renewable Energy. 1984. Appropriate Technology Small Grants Program Evaluation. Washington, D.C.: U.S. Department of Energy. March.

Carroll, H. R., and J. J. Angelo. 1983. Energy-efficiency improvement by raw-material use. Ceramic Engineering and Science Proceedings 4(3-4):258-269.

Central Transportation Planning Staff. 1983. Energy Contingency Plan for the Boston Region. Boston, Mass.: Central Transportation Planning Staff.

Clark, W. E., and W. S. Fleming. 1983. The Energy Management and Control System Selection Process: The Critical Components. Energy Technology 10. Washington, D.C.: Government Institutes Inc., June.

Conference on Energy Conservation in Buildings--Heating, Ventilation and Insulation. 1983. Electronic heating control system. Pp. 99-110 in Proceedings of the Contractors' Meetings, Brussels, edited by F. Fonzi, P. Segalini, H. Ehringer, G. Hoyaux, and P. Zegers. Dordrecht, Netherlands: D. Reidel.

Crane, L. H., and D. B. Hack. 1984. Energy Conservation Programs and Policies: An Overview of Technological Options and Related Implementation Strategies. Washington, D.C.: Congressional Research Service. March 11.

Darmstadter, J., H. Landsberg, and H. Morton. 1983. Energy Today and Tommorow. Englewood Cliffs, N.J.: Prentice-Hall.

Department of Energy. 1984a. Energy Conservation Multi-Year Plan, FY 1986-FY 1990. Washington, D.C.: U.S. Department of Energy. July.

Department of Energy. 1984b. A Synthesis of Technology Transfer Methodologies: Proceedings of the Technology Transfer Workshop, May 30, 31, and June 1. Washington, D.C.: Department of Energy.

Department of Energy, Office of Conservation and Solar Energy. 1980. Predesign Energy Analysis--A New Graphic Approach to Energy Conscious Design for Buildings. Washington, D.C.: U.S. Department of Energy. September.

Energy Conservion and Utilization Technology Materials Panel. 1985. Recommendations. Cincinnati, Ohio. Department of Energy.

EG & G Idaho, Inc. 1984. Assessment of Ceramic Materials Technology for Heat Exchangers. Idaho Falls: EG & G Idaho, Inc.

Ellenwood, S. 1985. Daylighting and Energy Use Prediction Techniques: Two Case Studies. General Proceedings. Conference on Research and Design 1985: Architectural Applications of Design. American Institute of Architects. March.

Ellsworth, D. A., R. H. Brownlee, W. Sydney, R. Selby, R. Wright, and L. Wickre. The oasis 2000 model: a rural earth-sheltered energy park. Underground Space 6:153.

Emery, A. F., D. R. Heerwagen, C. J. Kippenhan, S. V. Stoltz, and G. B. Varey. 1977. The optimal energy design of structures by using the numerical stimulation of the thermal response with emphasis on the passive collection of solar energy. Energy and Buildings 1(4):367-382.

Executive Office of the President, Office of Emergency Preparedness. The Potential for Energy Conservation--A Staff Study. Stock No. 4102-0009. Washington, D.C.: U.S. Government Printing Office.

Falk, N. 1983. Effective Use of Daylighting. Energy Technology 10, Washington, D.C.: Government Institutes, Inc. June.

Fassbender, A. G. 1983. Selected Energy Efficient Industrial Technology in Europe and Japan. Richland, Wash.: Battelle Pacific Northwest Laboratory.

Federal Energy Administration. 1974. Project Independence Blueprint. Washington, D.C.: U.S. Government Printing Office.

Fenton, S. E., R. L. Hershey, and A. M. Letzt. 1983. Electricity use impact of industrial robots. Pp. 4-50, Vol. 1, Proceedings of the RI/SME Industrial Robots International. 13th Symposium/Robots 7 Conference, Chicago, April 17-21, 1983. Washington, D.C.: Science Management Corporation.

Ferber, M. K., and V. J. Tennery. Evaluation of Tubular Ceramic Heat-Exchanger Materials in Basic Coal Ash from Coal-Oil-Mixture Combustion. Oak Ridge, Tenn.: Oak Ridge National Laboratory.

Gallyas, M. 1983. Wear testing of fine ceramic grinding bodies by tracer techniques. Epitoanyag 35(1):8-14.

Georgia Technology Institute. 1974. Technological Innovation: A Critical Review. Washington, D.C.: National Science Foundation.

Gill, B., J. M. Quets, T. A. Taylor, and R. C. Tucker, Jr. Use of plasma and D-gun ceramic and cermet coatings in gas turbines increases. Modern Power Systems 3(4):42-44.

Grande, M., G. Moss, S. Milwards, and S. Saich. 1983. The application of thin film wavelength-shifting coatings of perspex to solar energy collection. J. Phys. D. 16(12):2525-2535.

Guha, M. K. 1983. Economic/Reliability Trade-Offs in Materials Selection for Electric Power Generation Processes. Energy Technology 10, Washington, D.C.: Government Institutes Inc. June.

Harmon, A. J. 1980. Industrial Innovation and Government Policy: A Review and Proposal Based on Observation of the U.S. Electronics Sector Technological Forecasting and Social Change. Vol. 18, pp. 15-37. Amsterdam: Elsevier North Holland.

Hane, G. J., T. A. Williams, and S. G. Hauser. 1984. Review of Studies of Research Opportunities in Energy Conservation. Richland, Wash.: Battelle Pacific Northwest Laboratories.

Haus der Technik. 1981. Ceramic High-Temperature Fibres for Insulating Industrial Furnaces. HDT Meeting: Energy Storage Systems, Essen, Germany, May 1981. Essen, Germany: Vulkan-Verl.

Hershey, R. L., and A. M. Letz. 1983. Contributions of Robotics to Industrial Productivity Improvement. Energy Technology 10. Washington, D.C.: Government Institutes, Inc. June.

Holden, C. 1980. Innovation: Japan races ahead as U.S. falters. Science, 210:751.

Hubbert, L. King. 1969. Energy resources. Resources and Man. Washington, D.C.: National Research Council.

Hubbert, L. King. 1982. Energy Resources. Prepared for the Committee on Natural Resources, National Research Council. Washington, D.C.: National Research Council.

Illinois Department of Energy and Natural Resources. 1983. Options for Energy Efficiency in the Residential Sector: 1983-2000. Illinois Energy Plan, Volume 8. Springfield: Illinois Department of Energy and Natural Resources.

Karlov, N. V., A. N. Orlov, Y. N. Petrov, and A. M. Prokhorov. Energy efficiency of the laser control of gas diffusion through capillaries. Sov. Tech. Phys. Lett. 9(6):299-300.

Kedward, K. T. 1981. Joining of composite materials. P. 187 in American Society for Testing and Materials Special Technical Publication ASTM Symposium on Joining of Composite Materials, Minneapolis, Minn. April 1980.

Kelly, P. and M. Kranzberg. 1975. Technological Innovation: A Critical Review of Current Knowledge. Washington, D.C.: National Science Foundation. February.

King, C. R. 1978. Fibrous insulation heat-transfer model. Pp. 281-292 in American Society for Testing and Materials Special Technical Publication No. 660.

Kirkwood, T. F., and A. D. Lee. 1975. A Generalized Model for Comparing Automobile Design Approaches to Improve Fuel Economy. Santa Monica, Calif.: Rand Corporation.

Kosar, B. H. 1984. Energy Economics of Design Options. Microcomputer Program for IBM-PC Derived from CIRA Program. Product Literature. Butler, Pa.: Rittlemann Associates.

Kuehn, T. H., and E. A. B. Maldonado. 1981. A finite difference transient heat conduction program for studying the thermal performance of composite building envelopes. Pp. 265-276 in Building Energy Management--Conventional and Solar Approaches, F. E. de Oliveica, ed. Oxford: Pergamon Press.

Larsen, R. P. and L. R. Johnson, 1984. Ceramic Turbochargers: A Case Study of a Near-Term Application of High-Strength Ceramics. (CUNY/CNSV-47). Argonne, Ill.: Argonne National Laboratory.

Landsberg, H. H. 1979. Energy--The Next Twenty Years. A Report Sponsored by the Ford Foundation. Cambridge, Mass.: Ballinger.

Lawrence, R. F. 1983. A World of Progress in T&D. Energy Technology 10. Washington, D.C.: Government Institutes.

Los, S., S. Yannas, L. Agnoletto, and A. Bowen. 1983. Energy control in building design: an applicative graphic method. Pp. 827-836 in Proceedings of the International Conference on Passive and Low Energy Architecture. Chania, Crete, June 1983. Oxford: Pergamon Press.

Low, N. M. P. 1983. Glass-mica composite: New structural thermal-insulating material for building applications. Pp. 715-729 in American Society for Testing and Materials Special Technical Publication No. 789.

Lundstedt, S. B. and W. E. Colglazier, Jr. 1982. Managing Innovation: The Social Dimensions of Creativity, Invention and Technology. Oxford: Pergamon Press.

Mallog, J. 1983. Development of Adjustable Low Power Vaporizing Burners With High Energy Efficiency. Bonn-Bad Godesberg, Germany: Bundesministerium fur Forschung und Technologie.

Mansfield, E., A. Romeo, M. Schwartz, S. Wagner, and P. Brach. 1982. Technology Transfer, Productivity and Economic Policy. New York: W.W. Norton.

Marcus, G. H. 1985. Federal Energy R&D: President Reagan's First Four Years. Washington, D.C.: Congressional Research Service.

Marlay, R. C. 1984. Trends in industrial use of energy. Science 226:1277.

Maskalick, N. J., E. S. Buzzelli, D. Zuckerbrod, M. Bonner, and A. Mezzina. 1984. Hydrogen Production Employing High-Temperature Solid Oxide Cells. Proceedings of the Intersociety Energy Conversion Engineering Conference. San Francisco, Calif.; August 1984. Pittsburgh, Pa.: Westinghouse Electric Corporation.

Michaelis, M. 1984. Lessons from the 60s and 70s. DOE: A Synthesis of Technology Transfer Methodologies. Washington, D.C.: Department of Energy. June 1.

Mirkovich, D. 1983. Light plenum concept in office building design. In Progress in Passive Solar Energy Systems. American Solar Energy Society.

Morison, E. E. 1966. Men, Machines and Modern Times. Cambridge, Mass.: MIT Press.

Mozurkevich, M. and R. S. Berry. 1981. Finite-Issue Thermodynamics: Engine Performance Improved by Optimized Piston Motion. Proceedings Nat. Acad. of Sci.

Mozurkevich, M. and R. S. Berry. 1982. Optimal paths for thermodynamic systems. Applied Physics 53:34.

Myers, J. G. and L. Nakamura. 1978. Saving Energy in Manufacturing. Cambridge, Mass.: Ballinger.

Nall, D. and D. B. Crawley. 1983. Energy simulation in the building design process. Journal of the American Society of Heating, Refrigeration and Air-Conditioning Engineers 25(11):28-32.

Natarajan, C. P. and G. G.Homoki. 1983. Waste Heat Recovery, A Review of Hardware and Applications. Energy Technology 10. Washington, D.C.: Government Institutes.

National Academy of Engineering. 1974. Pp. 24-31 in U.S. Energy Prospects: An Engineering Viewpoint. Washington, D.C.: National Academy of Sciences.

National Conference of States on Building Codes and Standards, Inc. 1984. Energy Conservation Program for States and Localities. Herndon, Va.: National Conference of States on Building Codes and Standards.

National Technical Information Service. 1983. Electron Beam Curing of Polymers. 1977-February 1983 citations from the Rubber and Plastics Research Association Data Base. Springfield, Va.: National Technical Information Service.

Nelson, K. P. 1983. Energy Control System Specification. Energy Technology 10. Washington, D.C.: Government Institutes, Inc. June.

Newman, D. K. and D. Day. 1975. The American Energy Consumer. Cambridge, Mass.: Ballinger.

Nielsen, O. S. 1982. Research application in energy efficient design. Energy Conservation in the Built Environment, edited by P. Minogue. Dublin: An Foras Forbartha.

North Atlantic Treaty Organization. 1973. Technology of Efficient Energy Utilization. Brussels: North Atlantic Treaty Organization, Scientific Affairs Division.

Oak Ridge National Laboratory. 1985. Progress Report of the Materials Project of the ECUT Program. April 1 - June 30, 1985. Oak Ridge, Tenn.: Oak Ridge National Laboratory.

Office of Technology Assessment, Organizing Committee for the Federation of Materials Societies. 1970. Engineering Implications of Chronic Materials Scarcity. Stock No. 052-003-00344-9. Washington, D.C.: U.S. Government Printing Office.

Office of Technology Assessment. 1983. Industrial Energy Use. Washington, D. C.: Office of Technology Assessment.

Ohtsuka, M., Y. Iwasaki, T. Nishiyama, K. Abe, and T. Ukou. New heat pump pac for office use eliminated electric heaters. Refrigeration 58(668):621-630.

Okubo, T., and K. Takamoto. 1983. Pattern fidelity in submicron lithography with a rectangular electron beam. Japan Journal of Applied Physics Pt. 1 22(8):1335-1341.

Phillips, A. J. 1981. Thermal transmittance and conductance of roof constructions incorporating fibrous insulation. Pp. 479-501 in American Society for Testing and Materials. Special Technical Publication No. STP-789.

Poulis, P. D., S. Yannas, and A. Bowen. 1983. Centralized buildings control systems for energy management. Pp. 807-810 in Proceedings of the International Conference on Passive and Low Energy Architecture, Chania, Crete, June 1983. Oxford, England: Pergamon Press.

Quadrel, R., and W. Kroner. 1985. Intelligent Energy Graphics: Expert System Building Energy Analysis. General Proceedings. Conference on Research and Design 1985: Architectural Applications of Design. Washington, D.C.: American Institute of Architects. March.

Quick, J. P., and S. J. Irving. 1982. Computer simulations for predicting building energy use. Energy Conservation in the Built Environment, edited by P. Minogue. Dublin: An Foras Forbartha.

Qureshi, A. S. 1981. Low temperature heat recovery. Advances in Energy Utilities Technology. Atlanta, Ga.: Fairmont Press.

Reed, J. E., and C. R. Fink. Survey and Analysis of Materials Research and Development at Selected Federal Laboratories. Columbia, Md.: Energetics.

Rosenfeld, R. B. 1981. The development and philosophy of the photographic division's office of innovation system. Pp. 105-139 in Creativity Week IV: 1981 Proceedings, edited by S. S. Gryskiewicz and J. T. Shields. Center for Creative Leadership.

Ross, M. A., and R. H. Williams. 1975. Assessing the Potential for Fuel Conservation. Albany, N.Y.: The Institute for Public Policy Alternatives, State University of New York.

Roussel, A., and L. Haag. 1982. Application of microwave heating and hot air for the continuous production of plasticized PVC sheets. Proceedings of the CEC (Reidel) Applications and Techniques Contractors Conference. Brussels. Luxembourg, Belgium: Eurofloor Sa.

Schacht, W. H. 1985a. Industrial Innovation: The Debate over Government Policy. Washington, D.C.: Congressional Research Service.

Schacht, W. H. 1985b. Stevenson-Wydler Technology Innovation Act: A Federal Effort to Promote Industrial Innovation. Washington, D.C.: Congressional Research Service.

Schacht, W. H. 1985c. Technology Transfer: Utilization of the Results of Federally Funded Research and Development. Washington, D.C.: Congressional Research Service.

Scharnweber, D. H., and D. T. Vukovich, eds. 1980. Laboratory Evaluation of Ceramic Coatings for Diesel Exhaust Valves. Southfield, Mich.: Eaton Corporation.

Schurr, S. H. 1979. Energy in America's Future. Baltimore, Md.: Johns Hopkins University Press.

Shoda, M., and Y. Ishikawa. 1983. Monitoring and thermochemical analysis of fermentation process with a calorimeter. Pp. 33-41 in Modeling and Control of Biotechnical Processes, Proceedings of the 1st IFAC Workshop, Helsinki, August 17-19, 1982. Oxford: Pergamon Press.

Smith, W. W. 1983. Conservation and Load Management: An Alternative to New Generation. Energy Technology 10. Washington, D.C.: Government Institutes, Inc. June.

Soderstrom, E. J., and M. L. Rorke. In press. Evaluation of the Energy-Related Inventions Program-An Update for FY 84.

SYRSOL. 1985. A Building Energy Design, Analysis, and Simulation Program Intended for Architects, Engineers, Consultants, Builders, Researchers, and Universities. Syracuse, N.Y.: SYRSOL.

Sussock, H. 1982. Goal: A computer based model for integrated evaluation of energy and cost of building sketch designs. Energy Conservation in the Built Environment, edited by P. Minogue. Dublin: An Foras Forbartha.

Timoney, S. G. 1983. No-Coolant Diesel Engine. Dublin: University College.

Toscano, W. M., D. H. Walker, and R. D. Tetreault. 1983. Research and Development of Highly Energy-Efficient Supermarket Refrigeration Systems. Vol. 2. Supplemental Laboratory Testing. Waltham, Mass.: Foster-Miller Associates.

University of California, Lawrence Berkeley Laboratory. 1982. CIRA 1.0 Reference Manual. Contract DE-AC03-765F0098. U.S. Department of Energy. Washington, D.C.

University of California, Lawrence Berkeley Laboratory. 1982. CIRA 1.0 Based Energy Analysis and Auditing Program for Residential Buildings. Reference Manual. Berkeley, Calif:. University of California, Lawrence Berkeley Laboratory.

van Rijswijk, F. G. W. 1983. The cold accumulator: a way to improve the energy efficiency of refrigeration machinery. Koeltechniek 76(4):75-77.

Veyo, S. E. and T. J. Fagan. 1983. Advanced Electric Heat Pump Dual-Stroke Compressor and System Development. Pittsburgh, Pa.: Westinghouse Electric Corporation.

Walcoff, C. R. P. Ouellette, and P. N. Cheremisinoff. 1983. Techniques for Managing Technological Innovation. Ann Arbor, Mich.: Ann Arbor. Science

Westbrook, J. H., and F. F. Ling. 1975. Essay on Materials Conservation. Washington, D.C.: Office of Technology Assessment.

Wilson, R. W. 1980. Survey of the contribution of the metallurgist to tribology. Lubrication Engineering 36(5):263-269.

Zander, H. P. 1983. Lower energy costs in the ceramics industry--via ceramic fibers. Ceramic Forum International/Berichte der DKG (formerly Ber. Dtsch. Keram.) Ges. 60(2/3):85-88.

APPENDIX A

ABBREVIATED RESUMES OF COMMITTEE MEMBERS

COMMITTEE MEMBER	FIELD	RESEARCH	AFFILIATION
R. Stephen Berry	Physical chemistry	Atomic and molecular processes, thermodynamics resource management	University of Chicago, Department of Chemistry
David Bullen	Architecture	Energy conservation engineering	American Institute of Architects
Paul P. Craig	Physics	Energy policy, alternative energy strategies; energy conservation; cryogenics	University of California, Davis
Ralph C. D'Arge	Physics	Energy conservation, economics	University of Wyoming, Department of Economics
Bernard H. Kear	Materials science	Metallurgical science	Exxon Research Engineering Co.
Leon Glicksman	Mechanical engineering	Thermodynamics, heat transfer	Massachusetts of Institute of Technology, Department of Chemical Engineering
J. Laurence Kulp	Geochemistry nuclear science, and forestry	Geochemistry, radio-chemistry, and forestry	National Acid Precipation Assessment Program
Joel M. Leathers	Chemistry	Chlorination of saturated hydrocarbons	Dow Chemical U.S.A.

Fred H. Poettmann	Chemical engineering	Reservoir mechanics, natural gas engineering	Colorado School of Mines
Bernard I. Spinrad	Physics, nuclear engineering	Physics of nuclear reactors nuclear systems, energy systems and economics	Iowa State University

APPENDIX B

STATEMENT OF TASK

The committee will undertake the following tasks:

Task 1. A Reexamination of the Energy Conservation Rationale. (In the recent past the role and importance of energy conservation has been addressed extensively in professional journals, the open literature, and published books on energy and energy-related matters. It is generally accepted that energy conservation is in economic competition with energy sources as a way of making energy available.) Prepare a statement, in light of the above, as to the efficacy of past conservation measures; the potential utility of future conservation emphases; and the relative importance of conservation--among other approaches--to the energy future of the nation. This statement will serve to motivate the performance of Tasks 2 and 3, by calling attention to the relative stakes and the relative potential of efforts to find new conservation measures.

Task 2. Identification of Technical Needs. Identify existing energy systems where major energy savings could be realized, were it not for the lack of certain technological tools, developments, or solutions; catalog needed developments and solutions in various technical fields, that could have major impact in energy conservation vis-a-vis given systems. Areas of special interest include energy storage, conversion, and transmission. Attention will be paid to the likely cost-effectiveness of developments in these areas. The result of this effort will be a list of technological challenges which, if met, could result in major cost-effective energy gains through conservation.

Task 3. Generically Different, Potentially New Energy Systems. Identify emerging scientific or technical developments that could be enlisted to create generically new energy systems, with greatly enhanced energy conservation potentials; catalog such developments and speculate on the types of energy systems that might benefit from them, with attention given to their likely cost-effectiveness. Again, the areas of special interest are energy storage, conversion and transmission. It is expected that the principal emphasis of the study will be on this task.

Task 4. Nontechnical Incentives for Conservation. For completeness, describe, but not analyze, nontechnical incentives to conserve energy, such as the imposition of taxes, the promulgation of standards, the requirements of reporting, and the administration of regulations.

APPENDIX C

WORKSHOP AGENDA

AGENDA

WORKSHOP ON INNOVATIVE CONCEPTS AND APPROACHES TO ENERGY CONSERVATION
December 17-18, 1984

MONDAY, DECEMBER 17, 1984

(Lecture Room, National Academy of Sciences,
2101 Constitution Avenue, N.W.
Washington, D.C. 20418)

9:00 a.m.	Introductory Remarks
	R. Stephen Berry, University of Chicago
9:15	Energy Conservation in Industry
	Overview: Charles Berg, Northeastern University Research on Industrial Processes: Marc Ross, University of Michigan The Chemical Industry: Joel M. (Levi) Leathers, Dow Chemical Company
11:00	Coffee Break
11:15	Energy Conservation in Transportation
	Overview: William Garrison, University of California, Berkeley, Diesel Technology: W.T. Lyn, Commins Engine Company Isothermal and Adiabatic Engines: Stirling Colgate, Los Alamos National Laboratory
12:30 p.m.	Lunch
1:30	Energy Conservation in Transportation (continued)

2:30	<u>Energy Conservation in Buildings</u> Overview: Richard Stein, The Stein Partnership Observations: A.H. Rosenfeld, Lawrence Berkeley Laboratory
3:30	Coffee Break
3:45	Lighting in Buildings: Samuel Berman, Lawrence Berkeley Laboratory
4:15	<u>Scientific and Technological Innovations Applicable to Energy Conservation</u> Physical and Electro-Chemistry: John Bockris, Texas A&M University Ideas from Basic Chemistry, Combustion Process: Sydney Benson, University of Southern California
5:00	Adjourn

TUESDAY, DECEMBER 18, 1984

(Conference Room 356, Joseph Henry Building,
National Academy of Sciences
2100 Pennsylvania Avenue, N.W.
Washington, D.C.)

8:30 a.m.	<u>Scientific and Technological Innovations Applicable to Energy Conservation</u> (continued) Ceramic Engineering: James Mueller, University of Washington Materials Science: Brian Frost, Argonne National Laboratory Analytic Tools for Energy Conservation: R. Stephen Berry, University of Chicago Robotics: Gerald Michel, Arthur D. Little, Inc.
12:00 Noon	Lunch
1:00 p.m.	<u>PANEL COMMENTARY</u> David White, Massachusetts Institute of Technology Robert Whitford, Purdue Center for Public Policy

PANEL COMMENTARY (continued)

Henry Kelly, Office of Technology Assessment
Howard Hagler, Hagler, Bailly and Company
James H. Porter, Energy and Environmental Engineers, Inc.
Richard Schorr, Liebert Corporation

2:30	Group Discussion
4:00	Closing Comments, R. Stephen Berry, Chairman