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An Overview of Energy Conservation Research Opportunities

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December 1981

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

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Richland, Washington 99352

PREFACE

This document is a study of research opportunities that are important to developing advanced technologies for efficient energy use. The study's purpose is to describe a wide array of attractive technical areas from which specific research and development programs could be implemented. Research areas are presented for potential application in each of the major energy end-use sectors. The analysis is unique in that it employs a systematic process for both identifying and screening candidate energy conservation research areas. The study team was comprehensive in its review of aggregate energy consumption and employed explicit criteria to evaluate the technology research areas.

This study was completed for the Division of Energy Conversion and Utilization Technologies (ECUT) in the Department of Energy. The division's mission is to identify and research long-range technology concepts that are attractive for more efficient energy use. To meet its goals, the ECUT staff has established a planning and systems analysis project that was responsible for conducting this study.

This report is one of a series of studies in support of the ECUT research planning effort. Other documents in the series contain assessments of energy conservation technology areas, methods to appraise research projects for support, and data reference sources. Publications from this project include:

Hopp, W. et. al. 1981. Identification of Energy Conservation Research Opportunities: A Review and Synthesis of the Literature. PNL-3966, Pacific Northwest Laboratory, Richland, Washington.

Hopp, W. et. al. 1981. An Overview of Energy Conservation Research Opportunities-Executive Summary. PNL-3944Ex.Sum., Pacific Northwest Laboratory, Richland, Washington.

U.S. Department of Energy. 1981. The 1981 ECUT Work Element Appraisal. DOE/CE-0024, U.S. Department of Energy, Washington, D.C.

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1.0 INTRODUCTION

Since the 1973 Arab oil embargo, energy policy has become an issue of intense public concern in the United States. Oil and natural gas prices have increased dramatically and will continue to rise as easily accessible supplies dwindle. Development of alternate fossil fuels and nuclear power as replacements will involve massive capital investments and will pose serious environmental and safety problems. The more benign energy sources, such as the solar technologies, offer great promise for the future but are limited or exceedingly costly. The many problems facing alternative energy supplies are making the reduction of demand through energy conservation a necessary cornerstone of an effective national energy policy.

Energy conservation can minimize both the cost and side effects of whatever supply options are pursued by limiting the amounts of energy that must be produced. In most cases, conserving energy is less expensive than producing it. And despite fears of cold houses and underpowered automobiles, many energy conservation improvements can be achieved with only minor lifestyle changes by applying modern technology to increase energy efficiency.

The use of technology has already resulted in significant improvements in energy efficiency. For example, because of new technology the average fuel economy of new automobiles increased from 13.9 miles per gallon to 18.6 miles per gallon between 1974 and 1977 (Murrel et al. 1976). Increased application of existing technologies can result in additional energy conservation and will almost certainly occur as energy prices rise and efforts are made to remove the social and institutional barriers to these technologies. In the longer term, further energy-efficiency improvements will depend on advanced energy technologies that are possible only through research and development (R&D). Because energy conservation is a critical long-term component of national energy policy, government support of energy conservation R&D is crucial. In response to this concern the Pacific Northwest Laboratory (PNL) contracted with the Department of Energy (DOE) to identify promising research areas for potential government support. In particular, this study examines the areas where applied research by the federal government offers significant energy conservation potential.

Implementation of an effective federal applied energy conservation research program requires careful planning. Many R&D projects, such as one leading to patentable processes or devices, will yield benefits that can be fully realized by a private firm in the near term. Such R&D does not generally require federal support. By funding research in areas that would be addressed by the private sector, the government either would be replacing private investment or inefficiently allocating resources that could be better used elsewhere in the economy.

In many cases socially cost-effective R&D will not be performed by the private sector. This form of market failure can occur for several reasons. First, patent protection for energy conservation processes is often not complete, particularly for innovative processes. Second, R&D may not lead to a directly salable product and therefore may not offer sufficient financial incentives to private firms. Third, some R&D may be too large scale or long term to be attractive to private industry. Fourth, the R&D may be considered simply too risky for any one firm to pursue, although the potential payoff from the research may be high. Finally, part of the R&D benefits may accrue in the form of lower prices for consumers or decreased probability of supply disruptions, benefits that are very valuable to society as a whole but which do not increase a business' profitability. This study focuses on research opportunities that most likely will not be addressed by private industry for the above reasons.

Because areas exist where federally funded applied energy conservation research is appropriate, these areas must be identified to formulate an effective federal research strategy. This identification is a complex task because effective applied research addresses both a technological need, as well as an energy conservation application. This difference sets it apart from effective basic research, which must address a gap in the technological knowledge base, but need not have a clearly specified application. Thus, basic research opportunities can be identified by consulting the appropriate research communities to locate gaps in the technological knowledge base. Identifying applied research opportunities, however, requires a systematic approach to consider both the technology needs and potential applications.

This study develops and applies a systematic approach to identifying and screening applied energy conservation research opportunities. To broadly cover

The main purpose of this study is to provide useful information about potential areas of applied energy conservation research. It is not intended to produce a recommended research agenda. Thus, the goal of the information development is to present appropriate information about each technology to provide a research program director with a rational basis for seeking specific research activities for funding. For the technologies selected as focus technologies, three types of information are desired: 1) a summary of the major technical barriers and example research opportunities with which to address these barriers to indicate appropriate areas for applied research, 2) a brief estimate of the energy conservation potential of research on the technology to allow comparison of technologies in terms of energy savings, and 3) an overview of existing research programs that address the technology to indicate whether or not the potential research areas are being adequately covered.

In estimating the energy conservation potential of performing research on a technology, the degree of conservation that could take place without the research should be considered. Existing technologies may be able to be applied to a given energy flow to reduce its size. The proper estimate of energy savings from development of a new technology is the additional energy savings beyond that possible with existing technology. Many studies overestimate the energy conservation potential of technologies by comparing them to technologies actually in use rather than state-of-the-art technologies.

When a particular technology's potential is considered, applications to other energy flows besides the one with which it was identified should be noted. For example, heat pumps might be identified with buildings space heating but could also be applied to industrial energy conservation. These multisector applications of the focus technologies are treated in Chapter 6 of this study.

Technologies categorized in the screening process as requiring further analysis do not generally need the fairly detailed types of information developed for the focus technologies because issues exist that need to be resolved before these technologies justifiably can be considered as research areas. For example, a technology may be classed as requiring further analysis the energy end-use sectors, this study develops useful information relating to the areas where federally funded applied research will most likely play an important role in promoting energy conservation. This study is not designed to produce a detailed agenda of specific recommended research activities. The general information presented allows uniform comparisons of disparate research areas and as such provides the basis for formulating a cost-effective, comprehensive federal applied energy conservation research strategy.

Chapter 2 in this study discusses the various methodologies that have been used in the past to identify research opportunities and details the approach used here. In Chapters 3, 4, and 5 the methodology is applied to the buildings, transportation, and industrial end-use sectors and the opportunities for applied research in these sectors are discussed. Chapter 6 synthesizes the results of the previous three chapters to give a comprehensive picture of applied energy conservation research opportunities across all end-use sectors and presents the conclusions to the report.

2.0 METHODOLOGY

Producing a list of research ideas that support energy conservation is not difficult. The literature is replete with collections of people's "pet" research projects. However, simply compiling a set of research ideas does not insure that the set comprehensively covers the range of possible energy conservation opportunities, nor does it necessarily produce ideas that address critical research needs in the various research disciplines. To produce a comprehensive, well-justified list of research opportunities, a systematic identification methodology is necessary. This section discusses the various methodologies that have been applied in other studies to identify energy conservation research opportunities and details the methodology developed and used in this study.

Identifying a set of applied research opportunities to promote energy conservation requires knowledge of both the technical research disciplines and the energy end-use sectors. Without an understanding of the status of the appropriate research disciplines, the research opportunities identified may be technically naive. Without information on energy in the end-use sectors, applications of research results that most likely will save energy cannot be identified. Procedurally, two distinct approaches, exploratory planning and normative planning,[a] use both types of information to identify research opportunities.

Exploratory planning starts with the inherent capabilities of the technology and plans forward in time to the potential applications (of which many may exist). To identify research opportunities, this approach begins with knowledge of specific types of research and looks for applications to conserve energy via the results of this research. Since technical problems are emphasized, exploratory planning tends to be pessimistic and ignore the possibility of breakthroughs.

Normative planning, on the other hand, starts with the desired end application and works backward in time to define the technology developments

(a) Exploratory is variously called roll-forward, bottom-up, push-type, and capabilities-oriented. Normative is variously called roll-backward, top-down, pull-type, and needs-oriented.

required to satisfy that application. To identify research opportunities, this approach begins with the goal of energy conservation in specific end uses and looks for research activities that will facilitate this energy conservation. Normative planning tends to accentuate the possible with the assumption of timely developments.

Neither the exploratory nor the normative approach is a complete planning technique by itself. Exploratory planning alone can cause program opportunities to be overlooked and normative planning by itself can lead to grossly infeasible program strategies. Thus, actual planning efforts should make use of both approaches in an iterative process.

The exploratory approach is most commonly used to identify energy conservation research opportunities in the literature. In a companion study that formally reviewed and synthesized several research opportunities studies, the most frequently encountered method was simple presentation of a "laundry list" of "self-evident" good ideas (Hopp et al. 1981). Polling a group of experts to develop a list of ideas was the second most common method. In both cases, ideas were generated by persons familiar with a research discipline. While both types of study contain a wealth of diverse ideas, no unifying theme was apparent that forced the research ideas to focus on the most promising energy conservation areas.

Use of a normative approach to research opportunties identification in the literature was generally found in studies with a very narrow end-use focus, or in studies that dealt with research opportunities at a very general level. For example, a study of energy conservation in the steel industry might use a normative approach by first identifying the stages in the steelmaking process where energy efficiency improvements are possible and then targeting their search for research opportunities to address these stages. Also, a study of the economy as a whole might begin with identifying major areas of energy use (e.g., automobile engines and buildings space heat) and then looking for major research areas (e.g. combustion research, tribology, insulation materials) that have potential energy conservation application to these end-uses. A study rarely attempts to cover the entire energy end-use spectrum and to identify detailed research opportunities.

The abundance of exploratory studies and the paucity of comprehensive normative studies clearly indicated that the most productive role for this study would be to synthesize the existing exploratory studies to provide a base of ideas and then to apply a normative exercise to systematically structure the ideas. Figure 2.1 is a schematic of the process that was used to accomplish this objective. Methodologically, this approach draws from the work of the American Institute of Physics (Wolfe 1975), Grey, Sutton and Zlotnick (1978) and Ross and Williams (1981). As shown in Figure 2.1, this study makes use of a four-stage normative or top-down approach: 1) a review of energy use in the end-use sectors, 2) identification of energy conservation technologies that address these flows, 3) a screening process to single out technologies that are promising research areas, and 4) an information development process to identify potential research activities and to estimate potential energy savings from the research.

More specifically, the process begins with a review of energy use in the buildings, transportation, and industrial end-use sectors. Very large or very inefficient[a] energy flows are then identified as "target energy flows" and are given heavier emphasis of analysis. As a first approximation the largest and most inefficient energy flows are logically assumed to offer the greatest energy conservation potential. Some smaller flows may offer significant energy savings but are deferred to future studies to concentrate on the large and inefficient flows first.

A set of focal points is needed to go from knowledge of the significant energy flows in the end-use sectors to the opportunties for research to improve the efficiency of these flows. In this study the focal points for the analysis are provided by identifying a broad list of energy conservation technologies that address the energy flows. To avoid ruling out unconventional innovative ideas, the term "technologies" is broadly defined here to include specific

(a) Inefficiency of an energy flow can be evaluated in terms of either the first or second law of thermodynamics. The first law gives an indication of how much energy is productively used in comparison to total input energy. The second law gives the ratio of the minimum thermodynamic energy required to do a task to the actual energy used. Because of its indication of the theoretical potential for energy conservation, the second law of thermodynamics is used in this study wherever appropriate. Further information on the second law is available in Ross and Williams (1981).

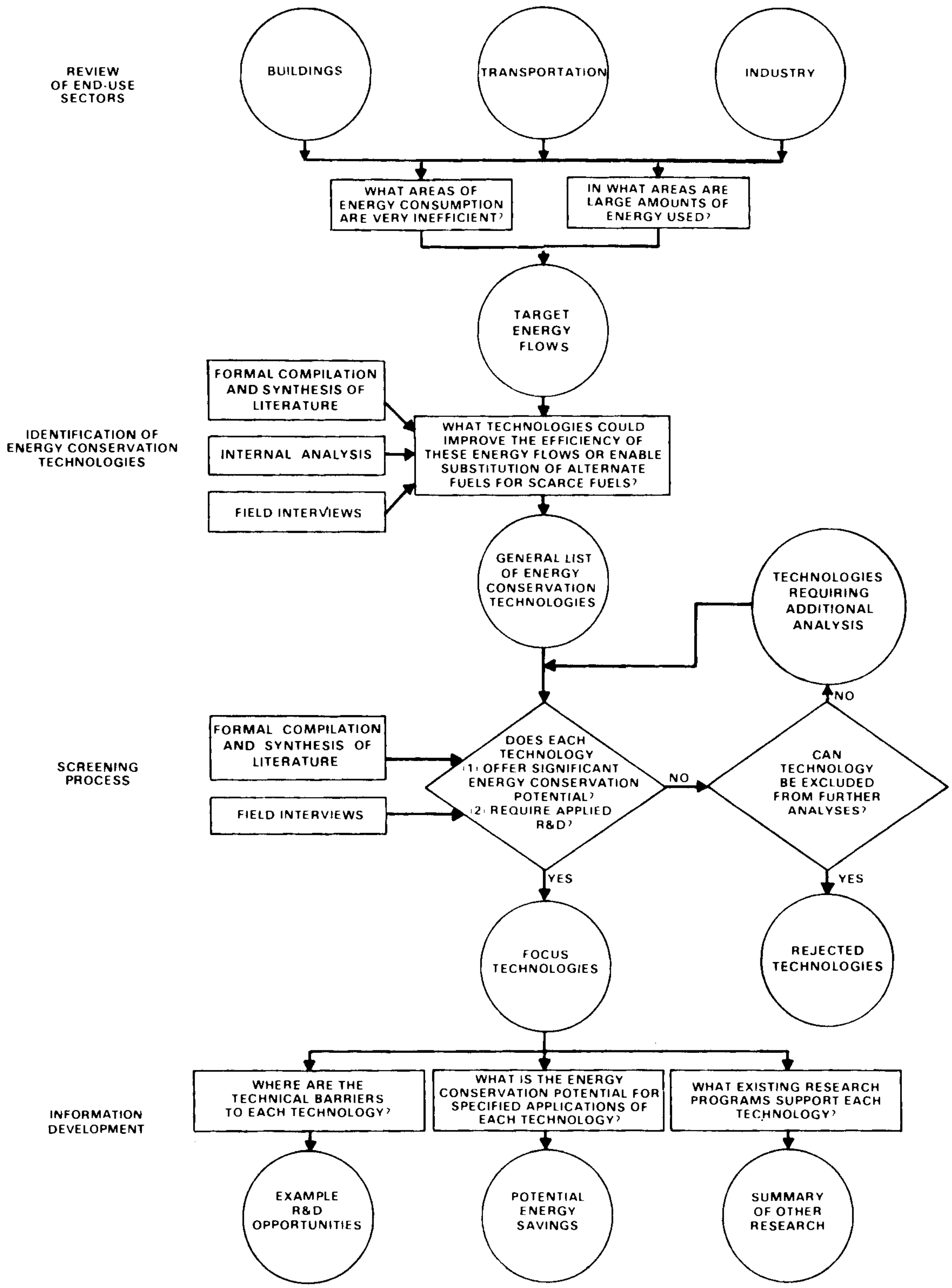

FIGURE 2.1. Process for Identifying Energy Conservation R&D Opportunities

devices (e.g., improved automobile engines), as well as general energy conservation concepts that do not necessarily hinge on a single device (e.g., substitution of communications for travel). One way to identify these energy conservation technologies is formal compilation and synthesis of the relevant literature. Specific details of this literature review process are presented in a separate document (Hopp et al. 1981). Internal analyses of the research staff and interviews of various experts are also used to generate ideas of potential energy conservation technologies.

Once a broad list of energy conservation technologies has been developed, the list is screened. This step is necessary because the list of all possible energy conservation technologies is so large that information could not be developed on all of them. Focusing on technologies that address specific energy flows is one form of screening that limits the number of technologies to be considered in detail. In addition, two criteria are used to screen the conservation technologies: 1) Does the technology offer significant energy conservation potential (i.e., on the order of 0.1 Quads per year)? and 2) Would applied R&D on the technology play an important role in realizing its potential energy savings?

The screening process partitions the list of energy conservation technologies into three categories. First, technologies that can justifiably be argued to meet the two criteria are called "focus technologies" and are given the most attention in the information development process. Second, technologies that can justifiably be argued not to meet the two criteria are rejected and excluded from further analysis. And third, technologies that may or may not meet the two criteria are identified as areas where further analysis is needed to evaluate their potential. By distinguishing among these three groups of technologies, time and resources are effectively used in the information development stage by concentrating on promising technologies and not devoting undue effort to areas where the expected payoff is low. However, the screening process is not a strict ranking or prioritization process. Technologies that fall into the category requiring further analysis are not necessarily poorer areas for research support than the chosen "focus technologies;" inadequate information exists to justify them as promising areas at this time.

The main purpose of this study is to provide useful information about potential areas of applied energy conservation research. It is not intended to produce a recommended research agenda. Thus, the goal of the information development is to present appropriate information about each technology to provide a research program director with a rational basis for seeking specific research activities for funding. For the technologies selected as focus technologies, three types of information are desired: 1) a summary of the major technical barriers and example research opportunities with which to address these barriers to indicate appropriate areas for applied research, 2) a brief estimate of the energy conservation potential of research on the technology to allow comparison of technologies in terms of energy savings, and 3) an overview of existing research programs that address the technology to indicate whether or not the potential research areas are being adequately covered.

In estimating the energy conservation potential of performing research on a technology, the degree of conservation that could take place without the research should be considered. Existing technologies may be able to be applied to a given energy flow to reduce its size. The proper estimate of energy savings from development of a new technology is the additional energy savings beyond that possible with existing technology. Many studies overestimate the energy conservation potential of technologies by comparing them to technologies actually in use rather than state-of-the-art technologies.

When a particular technology's potential is considered, applications to other energy flows besides the one with which it was identified should be noted. For example, heat pumps might be identified with buildings space heating but could also be applied to industrial energy conservation. These multisector applications of the focus technologies are treated in Chapter 6 of this study.

Technologies categorized in the screening process as requiring further analysis do not generally need the fairly detailed types of information developed for the focus technologies because issues exist that need to be resolved before these technologies justifiably can be considered as research areas. For example, a technology may be classed as requiring further analysis due to a serious nontechnical barrier that could prevent use of the technology whether or not applied research is performed. In this case, analysis of the nontechnical barrier should be performed before detailed investigations of the research opportunities are conducted. Thus, for technologies in this category an attempt is made to develop information that characterizes both the reasons the technology may be promising and the reasons it may not be promising. This analysis will provide the basis for determining the nature of the additional analysis needed to evaluate these technologies.

For technologies that can justifiably be argued to not meet the two criteria in the screening process, the only appropriate information is the reasons for failure. Those reasons are sufficient to exclude them from further analysis. Care is taken not to be overly strict in using the screening process to reject technologies because significant uncertainty is associated with many of the technologies. The lack of strictness in the screening process in this study is consistent with the need to consider diverse energy conservation research options.

The methodology used in this study has several advantages. First, it forces systematic coverage of the end-use sectors to insure that no important areas of energy conservation opportunities are overlooked. Second, through the screening process it leads to efficient allocation of time and resources in the task of developing information pertaining to the various energy conservation technologies. The heaviest efforts are directed towards areas that offer the greatest promise. Third, by simply screening the technologies, rather than formally ranking them, the methodology avoids mechanical rejection of novel ideas that have not been extensively studied. Because the results of this study are intended to highlight areas that require additional analysis, as well as to identify areas of research opportunities, the methodology is able to incorporate uncertainty and imperfect knowledge. Finally, the approach of this study is designed to bring together a broad range of disparate ideas and to give them appropriate consideration under a consistent format. In this way, the study goes beyond the "laundry lists" that are so common in the literature and provides the first steps towards developing a rational system for comparing the relative worth of applied research into topics ranging across the entire energy conservation spectrum.

3.0 BUILDINGS

In 1978 77 million housing units existed in the United States, two thirds of which were single-family homes (U.S. Department of Commerce 1980). Energy use in residential buildings in 1977 represented 16 quads (10^{15} Btu). Commercial buildings used an additional 10 quads (Oak Ridge National Laboratory 1979). Together, residential and commercial buildings accounted for over 26 quads, or 35% of the total U.S. energy budget. This sizeable energy use in the buildings sector makes it a logical target for energy conservation efforts.

Table 3.1 shows a breakdown of energy by end use in residential and commercial buildings. The largest user of energy in both types of buildings is space heating, which accounts for almost half of total energy use. Smaller, although still significant amounts of energy are used in lighting, air conditioning, water heating, and refrigeration. A notable difference between residential and commercial buildings energy use is that residential buildings use 27% of their energy for water heating and refrigeration and only 6% for lighting. Commercial buildings, on the other hand, use 22% of their energy for lighting and only 3% for water heating and refrigeration. This usage indicates that lighting is an important energy conservation area in commercial buildings,

TABLE 3.1. Energy Consumption in the Residential/Commercial Sector, 1977 (10^{15} Btu) (Oak Ridge National Laboratory 1979)

End-Use	Residential	Commercial	Total
Space Heating	7.69	4.56	12.25
Lighting	0.96	2.33	3.29
Air Conditioning	1.10	2.19	3.29
Water Heating	2.26	0.23	2.49
Refrigeration/Freezers	2.13	0.11[(a)]	2.24
Cooking	0.83	0.30[(a)]	1.13
Other	1.15	0.64[(b)]	1.79
TOTAL	16.12	10.36	26.48

(a) 1975 Data.
(b) Estimated.

while energy conservation in water heating and refrigeration offers greater application to the residential sector.

Table 3.2 gives a breakdown of energy use by fuel type for residential and commercial buildings. Electricity is the most widely used source of energy, accounting for about half of the total. However, in the important end use of space heating, oil and gas account for 77% of energy use in residential buildings and 84% of energy use in commercial buildings (Oak Ridge National Laboratory 1979). Thus, space heating in buildings offers a promising area in which energy conservation could significantly reduce oil and gas consumption.

3.1 ENERGY CONSERVATION POTENTIAL

With the realization that energy use in buildings is substantial and offers a tempting target for conservation efforts, the question arises as to how much energy can realistically be saved. This is a complex question that hinges on many technical, economic, and social issues. However, to place the subsequent discussions of energy savings from R&D in perspective, an overall projection of buildings' energy use and potential savings is necessary. Such a projection involves consideration of both future energy-use efficiency in buildings and the size of the future building stock. The Committee on Nuclear and Alternative Energy Systems (CONAES) has developed a range of scenarios of future energy use in buildings (National Academy of Science 1979). These scenarios are reviewed here to provide a basis for this analysis.

TABLE 3.2. Distribution of Residential/Commercial Energy Use by Fuel Type, 1977 (10^{15} Btu) (Oak Ridge National Laboratory 1979)

Fuel Type	Residential	Commercial	Total
Electricity[a]	7.81	5.62	13.43
Natural Gas	5.30	2.39	7.69
Oil	2.40	2.00	4.40
Other	0.62	0.35	0.97
TOTAL	16.12	10.36	26.48

(a) Includes generation losses.

The CONAES study presented four scenarios of energy use in buildings in the year 2010, ranging from what they felt was a very low projection to a very high one. To arrive at these different scenarios several assumptions were necessary. The following assumptions were common to all the scenarios:

- U.S. population will grow from 214 million in 1975 to 279 million in 2010.
- Housing stock will increase from 70.4 million units in 1975 to 114.8 million units in 2010.
- GNP will increase by an average annual rate of 2% per year from 1975 to 2010.
- Single-family units will decline from 67 to 58% of total housing units, while multi-family units will increase from 29 to 34% of the total and mobile homes will increase from 4 to 7% between 1975 and 2010.
- Commercial floor space will increase from 26,600 to 55,000 billion square feet over the period from 1975 to 2010.

In addition to these general assumptions, each of the four scenarios is based on specific assumptions, as shown in Table 3.3. The differences in energy prices shown in this table have a significant effect on the amount of future energy use in buildings. The CONAES panel felt that Scenario B does not require any new technological developments. The appliance efficiencies, thermal integrities, and nonresidential buildings efficiencies that are assumed are all available or readily achieved. The energy improvements that occur are due to normal market response to higher energy prices. Leak plugging, flue dampers, heat pumps, more efficient air conditioners, reduced lighting levels, and improved appliances are used to improve buildings energy efficiency in this scenario. In Scenarios C and D, where energy prices are constant or decline, these measures are assumed to be applied to a much less degree. In Scenario A, the high energy prices cause higher market penetration of the best technologies assumed in Scenario B. Electric heat pumps are assumed to capture 90% of the electric heating market and today's highest energy efficiency rating (EER) air conditioners are assumed to capture the space-cooling market by 2000. Although the high energy prices in Scenario A would provide strong incentive for

TABLE 3.3. Specific Assumptions of Electricity, Gas and Oil Prices Used in Formulating the CONAES Scenarios (in constant dollars from 1975 to 2000)

	Electricity	Gas	Oil
Scenario A	+3.5[a]	+7.2	+4.6
Scenario B	+2.0	+5.0	+2.5
Scenario C	+0.0	+2.5	+0.0
Scenario D	-1.2[b]	1.0	-1.4

(a) + represents a price increase.
(b) - represents a price decrease.

adopting new technologies, the energy use projections by CONAES do not assume new technological developments.

Table 3.4 summarizes the projected energy use in the year 2000 for the four CONAES scenarios. Scenarios A and B show total energy use in buildings declining, despite a 63% increase in the number of residential housing units and a 107% increase in commercial floor space. Scenarios C and D show increases in buildings' energy use. However, despite substantial decreases in buildings' energy use in Scenarios A and B, the total amount of primary energy consumed to meet this use remains almost constant in Scenario A and actually increases in Scenario B. This situation is due to CONAES' assumption that the percentage of total energy use supplied by electricity increases in all scenarios. Conversion losses in electricity production account for the higher levels of primary fuel use.

Based on the previous discussion of future energy use scenarios for the buildings sector, a reasonable "base case" for the year 2010, given moderate real price increases, would seem to be that energy use in buildings will remain essentially constant between 1975 and 2010. This assumption is approximately equivalent to Scenario B. However, depending on the percentage of energy that is supplied in buildings by electricity, the fossil fuel inputs to provide this end-use energy could vary significantly.

A study by Resources for the Future (RFF) tends to substantiate the CONAES Scenario B but offers a different perspective on the issue of fuel mix (Schurr

TABLE 3.4. CONAES Scenarios of Energy Use in Residential and Commercial Buildings in 2010 (10^{15} Btu)

End Use	1975 Base	Scenario A	Scenario B	Scenario C	Scenario D
Space Heating	10.6	5.7	6.9	10.7	14.6
Air Conditioning	1.1	1.3	1.5	2.3	3.1
Water Heating	1.8	1.4	1.4	2.2	3.0
Refrigeration/Freezing	0.4	0.4	0.5	0.6	1.0
Cooking	0.5	0.3	0.4	0.5	0.7
Lighting	0.9	1.0	1.1	1.7	2.0
Other	1.0	1.1	1.2	2.3	2.4
TOTAL[a]	16.3	11.2	13.4	20.3	26.8
(Total Primary Input)[b]	(25.1)	(24.0)	(29.5)	(44.0)	(53.3)

(a) Electricity is converted at 3415 Btu/kWh and therefore does not include generation losses.
(b) Electricity is converted at 11,500 Btu/kWh to account for generation losses.

et al. 1979). The RFF study assumes that electric space heating would be installed only in smaller units, in units with better than average construction, or in those located in warmer climates. Under this assumption, RFF projects that space heating energy consumption in fossil fuel equivalent in the year 2000 would be 93% of 1975 levels if the present conservation policies are used. Space heating energy could rise to 129% of 1975 levels if a relative failure to meet conservation goals occurs, or could fall to 52% of 1975 levels if more aggressive conservation policies are pursued.

Because of the serious uncertainties involved in projecting future fuel mixes, this study follows the example of the RFF study and does not assume a shift toward electricity use in buildings. Rather, the total buildings' use in the year 2010 is assumed to be at approximately the levels shown in Tables 3.1 and 3.2 and will be met with a similar fuel mix. This level of energy use can be achieved without extreme lifestyle changes or technological advances. Lower levels of energy use in buildings are certainly possible given timely technology developments. The degree to which specific technology developments can reduce energy use in buildings below this base level is discussed in the following sections.

3.2 IDENTIFICATION OF BUILDINGS ENERGY CONSERVATION TECHNOLOGIES

The methodology used in this study, which is diagramed in Figure 2.1, concentrates on identifying research that will save energy in the largest and most inefficient end uses. This approach is based on the premise that in the absence of other information more energy is expected to be saved in large and inefficient uses than in smaller and more efficient ones. This premise certainly does not mean that smaller energy flows can never offer significant opportunities for energy conservation research, especially when the research has more than one application. However, because in-depth coverage cannot be given to all possible areas, this analysis focuses on energy uses most likely to offer the largest energy conservation payoffs.

Table 3.1 shows that space heating is the largest energy use in buildings, accounting for almost half of total energy use in buildings or 16% of total energy use in the United States. Space heating is also an inefficient use of energy. Present gas-fired furnaces have thermal efficiencies on the order of 0.6, while electric resistance heating has a thermal efficiency of about 0.3 (taking conversion losses into account). While these efficiencies may not appear particularly low at first glance, the second law of thermodynamics shows space heating to be very inefficient. The second law efficiency is defined as the thermodynamic minimum amount of energy required to perform a task divided by the actual energy required. Because space heating uses high-quality fossil fuels and electricity, which are capable of performing a great deal of work, to produce low-temperature heat, the second-law efficiency of space heating is estimated as only 0.06 (Wolfe 1975). Although a second-law efficiency of 1.0 is neither technically feasible nor economically attractive, this low second-law efficiency clearly indicates room for improvement.

Because of the magnitude and inefficiency of energy use for space heating, this end use is singled out as a "target energy flow" and is emphasized in this analysis. Although space heating probably offers the largest conservation potential of the energy end uses in buildings, the other end uses are by no means insignificant. Appliances in residences, including water heaters, refrigerators/freezers, and ranges/ovens, account for over 30% of household energy use. Water heaters are estimated to have second-law efficiencies of around 0.03, and refrigerators/freezers have second-law efficiencies of between 0.03 and 0.04 (Wolfe 1975). Because lighting accounts for 22% of total energy use in commercial buildings, residential appliances and commercial lighting are also emphasized in this study, although not to the same extent as space heating.

Given the relative importance of the various energy flows, a range of energy conservation technologies addressing these flows was generated (Table 3.5). These technologies were identified from the literature and through contacts with various experts and internal analysis by the staff working on this study. The list in Table 3.5 is by no means an exhaustive list of all possible energy conservation technologies. A much broader list of ideas is presented in the companion study to this one, which compiles the numerous ideas from several research opportunities studies. The smaller list in Table 3.5 contains the major conservation technologies that offer potential focal points for identifying research opportunities to promote buildings' energy conservation.

3.3 SCREENING OF BUILDINGS' ENERGY CONSERVATION TECHNOLOGIES

Once a general list of energy conservation technologies has been developed, the next step in the methodology shown in Figure 2.1 is to perform a screening process on the list. As discussed earlier, the screening process involves examining each technology to determine whether it can justifiably be argued to 1) offer significant energy conservation potential and 2) require applied R&D support. Relatively detailed information is then developed for technologies that meet these criteria. Inevitably, limitations in time, resources, and information will result in some technologies not being demonstrated to meet the two criteria when closer scrutiny may show them to be promising areas of research opportunities. In these cases, an effort is made to identify the type of additional analysis that is necessary to clear up the uncertainties of the technologies' potential.

TABLE 3.5. Buildings' Energy Conservation Technologies

SPACE HEATING	LIGHTING
Earth-Sheltered Housing	Light Pipes
Thermal Storage Materials	Automatic Controls
Thermal Diodes	Advanced Bulbs
Air-to-Air Heat Exchangers	
Grey Water Heat Recovery	**AIR CONDITIONING**
Adsorption Cycles	Absorption Cycles
Absorption Cycles	Adsorption Cycles
Improved Heat Pumps	Seasonal Thermal Energy Storage
Advanced Furnaces	Earth-Sheltered Housing
Waste-Heat Recovery	Thermal Diodes
Window Technologies	Air-to-Air Heat Exchangers
Localized (Task) Heating	
Air and Heat Recirculation	**REFRIGERATION**
Systems Controls and Sensors	Externally Cooled Coils
District Heating Systems	Waste-Heat Driven Cycles
Seasonal Thermal Energy Storage	Absorption Cycles
Combustion of Low-Quality Fuels	Adsorption Cycles
Retrofit Insulation	
	COOKING
WATER HEATING	Convection Ovens
Grey Water Heat Recovery	Microwave Ovens
Point-of-Use Heating	Advanced Ranges
Recirculation of Hot Water	
Water-Conserving Appliances	
Cold-Water Soaps	
Retrofit Insulation	

Some of the technologies listed in Table 3.5 can be argued not to meet the two screening criteria. In particular, the cooking technologies are probably not attractive for federal research support because cooking represents only slightly over a quad of annual energy consumption and therefore, improvements in efficiency do not offer massive energy savings. Also, even if an advance in microwave or convection cooking could be shown to offer reasonable energy savings, the benefits of such a development would be fully capturable by a private firm. Thus, this research would be best left to private industry.

In the area of water heating the largest energy savings would result from insulating the hot water tank, conserving hot water, and using solar water heating. Because solar heating is not considered a conservation technology it is not addressed in this study. Hot water conservation techniques, such as use of cold water soaps, point-of-use heating, hot water recirculation, and water-conserving appliances, are already on the market. While increased use of these technologies would result in significant energy conservation, applied R&D is not essential to insuring their use. The major problems facing these technologies appear to be social and institutional in nature. Any technological advances do not involve high-risk research and are therefore suited to industrial R&D. Increased insulation of new hot water tanks is a known technology that will almost certainly be adopted in the market as energy prices rise. Improved retrofit insulation for hot water tanks may involve some relatively short-term technology development. However, the relatively fast turnover rate of water heaters limits the conservation potential of retrofit insulation.

Grey water heat recovery is a technology that may offer promise. An average family of four uses approximately 150 gallons of heated water per day at an average temperature of 108^{o}F (Hopp and Darby 1980). This water represents a daily flow of energy, literally down the drain, of over 48,000 Btu per day (based on an interior temperature of 70^{o}F). If this energy could be recovered for space or water heating purposes for the entire year, it would amount to over 17 million Btu per year. For space heating the average housing unit uses 122 million Btu per year (Schurr et al. 1979), which is equivalent to 14% of the energy used in space heating. Clearly, all of the energy lost in hot water cannot be practically recovered. The extent to which grey water heat recovery can improve buildings' energy use efficiency, and the technology development that is needed to accomplish this requires further analysis before the appropriateness of federal research can be determined.

One final area that could reduce the amount of energy used to heat water is the concept of integrating the hot water heater with other appliances, such as the air conditioner or the refrigerator. This concept seems to offer energy conservation potential and is discussed in more detail in Section 3.4.5 on integrated appliances.

Refrigeration and air conditioning energy use can be reduced by reducing the cooling load or by improving the efficiency of the cooling system. Reducing a refrigerator's cooling load simply involves adding insulation and therefore does not need applied research. Reducing the air conditioning load in a building is generally similar to reducing the heating load. Insulation, thermal diodes, earth-sheltered housing, improved windows, thermal storage, and air-to-air heat exchangers can all be used to reduce heating and cooling loads. Since most houses in the U.S. use more energy for space heating than cooling, these technologies will be discussed below in reference to space heating.

Improving the efficiency of air conditioners and refrigeration systems could be accomplished through the use of alternative cycles. Absorption and adsorption cycles are potential alternatives to conventional refrigeration and air conditioning cycles. Adsorption cycles have been used in industrial chemical processes, primarily for dessication. The dehumidification capabilities of adsorption cycles may make them attractive in air conditioning cycles in areas where humidity is a problem. However, insufficient research has been done to determine the practicality and economic feasibility of adsorption cycle air conditioners. Further analysis is needed to evaluate this fairly long-term research option. Absorption cycle air conditioners and heat pumps also require much technology development to develop cost-effective devices. Absorption cycles are inherently costly and complicated and do not offer short-term advantages over conventional cycles. In the longer term, district heating and cogeneration may offer promising space heating and cooling applications for absorption cycles. Additional analysis of applying absorption cycles to waste heat use is necessary to evaluate their potential. Although absorption and adsorption cycles are not considered specifically as air conditioning technologies, some discussion relevant to these technologies can be found in Section 3.4.1 on advanced heat pumps and furnaces.

Lighting is a relatively large energy user, particularly in commercial buildings. Over 3 quads, mostly electricity, is used annually to provide lighting in buildings. Energy use could be decreased through reduced lighting levels and increased efficiency of lighting technologies. Applied research and technology development to promote energy conservation in lighting may offer promise and is discussed in further detail in Section 3.4.4 on lighting technologies.

Space heating, which accounts for over 12 quads of energy annually, offers enormous potential for energy conservation. Technologies already on the market, such as increased insulation, weatherstripping, heat pumps, night set-back thermostats, and movable window insulation, could be retrofitted to reduce fuel consumption in an average building by two thirds or more (Ross and Williams 1981). Thus, much of the energy conservation potential in buildings is not dependent on technology advances and because of higher energy prices should occur, given an appropriate social and institutional environment. Even if space heating energy use could be reduced by two thirds by promoting existing retrofit technologies and improved building techniques, the magnitude of energy use in space heating leaves room for applied R&D to result in significant savings beyond this. Reducing space heating energy consumption by two thirds would still leave over 4 quads of energy use, which could be addressed by applied research on the space heating technologies listed in Table 3.5, at the very minimum.

Four of the space heating technologies shown in Table 3.5 offer very large potential savings: retrofit insulation, earth-sheltered housing, district heating, and seasonal thermal energy storage. Retrofit insulation could easily cut energy use in existing buildings in half. However, the importance of applied research's role in this area is not clear. Retrofit insulation is already available on the market. Cost reduction could be one goal of applied research, but the labor intensiveness of retrofit insulation may limit the degree to which applied research could affect the consumer's cost. Alternatively, research into the problems of degradation and health impacts of various types of insulation may be promising research areas. However, the federal government must show that insulation vendors will not perform the needed research before federal research support can be justified.

Earth-sheltered housing could reduce space heating energy requirements by up to 80% in new housing. Unlike insulation, it is not applicable to retrofits. The housing stock scenario discussed in Section 3.1 projected that almost one half of the houses in the year 2010 would be new since 1975. Thus, the absolute maximum energy conservation potential of earth-sheltered housing is on the order of 40% of total space heating energy in the year 2000. However, serious social and institutional problems will probably limit the penetration of this technology to considerably less than 40%. Since applied research cannot affect the social and institutional barriers facing earth-sheltered housing, the R&D benefits are difficult to assess. These social and institutional issues must be faced before research support of earth-sheltered housing can be justified.

District heating, which uses waste heat from an industrial facility or a power plant to provide space heating for buildings, is feasible using present technology. District heating is already fairly widely used in Europe. One area in which research could improve district heating technology and reduce its cost would be development of systems to transport the waste heat via latent chemical instead of sensible thermal means. By transporting a chemical to the buildings from which heat is extracted, costly insulation of the transport pipes could be avoided. However, as the lack of district heating installations in the United States proves, significant institutional barriers to district heating exist, which must be examined before the potential for research support can be evaluated.

Seasonal thermal energy storage uses a heat pump to extract heat from a water tank or an underground reservoir during the heating season and then uses the tank or reservoir as a heat sink during the cooling season. The water heater and refrigerator can also be integrated into the system. Because of the high storage costs, this system may be more economical in community-scale configurations. Although this system offers large potential energy savings, it is not clearly in need of applied research. Rather, careful engineering development and removal of institutional barriers are probably the needed support tasks for this technology. Because DOE already has a large program to investigate seasonal thermal energy storage, it is not considered in detail in this study.

In a standard house about 25% of the heating and cooling load is due to heat transfer through the windows (Wolfe 1975). Weatherstripping, storm windows, and night insulation could reduce the energy flow through the windows by as much as 70%. The additional energy savings through applied research, such as development of selective surfaces or higher R-value windows, may not be large. However, if the developments are more socially acceptable than current alternatives, they may improve the market penetration of advanced windows. For example, development of high R-value windows (e.g., transparent insulation) not requiring the occupants' attention that is needed to effectively use movable insulation, might improve market penetration. Window vendors are actively pursuing many novel ideas that should be surveyed before federal research support is considered.

Air infiltration accounts for about 30% of the heating load in a typical house and more in a well-insulated house (Wolfe 1975). Typical air exchange rates are currently around one air change per hour. Exchange rates of 0.1 to 0.2 are possible through leak plugging. However, at these very low air exchange rates, indoor air quality may degradate to the point of causing a health hazard. A technology that allows very low air exchange rates while preserving the quality of indoor air is the air-to-air heat exchanger. This device exhausts the stale air but recovers the sensible heat in the air to preheat the incoming fresh air. Because so few houses are "tight" enough to face indoor air-quality problems, the application of air-to-air heat exchangers is rather limited. Also, air-to-air heat exchangers that are 70 to 80% thermally efficient are currently available at a cost of about $300 Shurcliff 1981). This price will almost certainly drop as the devices become more common. The payoff in terms of efficiency improvements or cost reduction from applied research would seem to be small.

Grey water heat recovery and other waste heat recovery techniques could reduce the amount of energy required in space heating. Grey water heat recovery, as discussed previously, may offer reasonable energy savings but does not clearly need applied research for development. The other most promising waste heat recovery technique for buildings is heat recovery from lights. This technology is particularly appropriate to fluorescent lights in commercial buildings, where the heat generated by lights is sufficient to supply most of the heating needs. In fact, many commercial buildings experience a cooling load in the winter as a result of heat from lights. Recovering this waste heat would involve circulating a fluid in the plenum above or around the lights and then circulating the heat to areas where it is needed or exhausting it if is not needed. This technology offers promise for reducing both heating and cooling energy in commercial buildings. However, adequate systems could be produced through sound engineering alone and therefore technology development through applied research is not required.

Air and heat recirculation is similar to the idea of waste heat recovery in buildings. In commercial buildings areas near the perimeter of the building often require heating, whereas areas near the center require cooling because of the heat generated by occupants and electrical devices. Some research into computer control techniques and improved filtering systems could favorably impact the technology of recirculating air and heat in a building. However, as in waste heat recovery, developing suitable systems is probably more a matter of engineering than applied research.

Localized or task heating involves the use of radiant heat to warm the occupants in a room, rather than using convective and conductive heat to warm the space in the room. This idea may have energy conservation potential, particularly in applications where relatively few persons occupy large spaces, such as workshops. However, radiant heaters are already on the market. Engineering improvements and appropriate application of this existing technology should achieve the conservation potential of task heating technologies.

As oil, gas, and electricity prices have risen in recent years, more households have turned to combustion of lower quality solid fuels, such as wood and coal, to provide part or all of their space heating requirements. Although the technology for burning these fuels is very old, applied research could possibly improve the viability of this option. In particular, the environmental problems associated with solid fuel burning devices need to be resolved before these devices can make their maximum contribution. Due to the fragmented nature of woodstove manufacturers, the needed research may not be performed by the private sector. Because of the potential magnitude of alternative fuels combustion to supply space heat for buildings and the apparent opportunity for research, this subject is considered in more detail in Section 3.4.2 on low-quality fuels combustion.

One of the most promising and economical conservation options for new housing is passive solar heating. This technology involves collecting solar heat through south-facing glass and storing that heat in some storage medium. At present, the most common storage materials are massive materials such as stone and cement, although some phase change materials, which store energy as the latent heat of a chemical reaction, are also used. The need to integrate large amounts of storage materials into an effective passive solar structure can cause aesthetic problems and also tends to make retrofits difficult. Appropriate applied research to improve thermal storage materials may be able to improve the viability of passive solar heating. Because of the large potential role for passive solar heating in the future, thermal storage materials, including the specific storage option of a thermal diode, are considered further in Section 3.4.3.

As mentioned in Section 3.1, the second-law efficiency of space heating is only about 0.06. This low efficiency results because gas furnaces and electric resistance heaters simply convert high-quality energy to low-temperature heat. This high-quality energy could be used to move or "pump" energy from a heat source (e.g., outside air, earth, or water) to provide space heat. Heat pumps work precisely in this way. Present heat pumps use electricity and are two to three times more efficient than electric resistance heating. Further developments of heat pumps would be increased efficiency and use of fossil fuels instead of electricity. Because of the broad applicability of heat pumps in conventional space heating applications, as well as in solar systems and seasonal thermal energy storage systems, heat pumps and advanced furnaces are examined more closely in Section 3.4.1. Absorption and adsorption cycles are also considered as potential heat pump technologies.

One final very important energy conservation technology for buildings is systems controls and sensors. Many of the other conservation technologies, such as waste heat recovery, heat recirculation, some integrated appliance schemes, and district heating, depend directly on some kind of control system. However, the applicability of systems controls and sensors to energy use in buildings goes beyond their role in facilitating the function of specific devices. To be effective the increasing complexity of energy-efficient buildings requires a higher level of integrated control than in the past. Many energy conservation innovations can be rendered ineffective by occupant practices and design failures. For example, windows are opened because of excessive temperatures or stuffy conditions; the air conditioner is used because windows are inadequately shaded against the sun; the refrigerator runs constantly because of inadequate ventilation of the condensing coils; and solar collectors leak or get covered with leaves and dirt. Avoiding these types of failures requires both improved control of energy systems in buildings and improved quality of information to the occupants. Use of systems controls and sensors can improve both control and information in buildings.

Optimization of a building energy system should be directed at making the building "smart." A "smart" building would have a system to measure and display relevant data concerning its energy systems. For instance, the system should show that "infiltration rate is 20% higher than yesterday" (perhaps because of an open window), and "air filter needs changing." In addition to supplying information, the "smart" house should automatically control all systems, or at least provide indications of necessary actions to achieve optimal thermal comfort. This control should be able to incorporate information from the occupants, indicating, for example, that a particular room is too hot, or that the house will be unoccupied for a given period. The system should be able to suboptimize the house's performance in the case of nonoptimal occupant behavior. For example, failure to change a filter might require increased ventilation to maintain adequate air quality at the expense of energy efficiency. The system should also be self calibrating and resistant to failure.

Development of a "smart" house will require sensors that have capabilities beyond those of a conventional thermostat. The sensors should be able to optimize comfort on the basis of humidity, air velocity, and activity level, as well as temperature. Developing these advanced sensors, information display systems, and control systems most likely will involve use of microprocessors.

Because research into microprocessors is currently a very "hot" area, with many private firms conducting research, a thorough survey of this area's state-of-the-art is necessary before specific recommendations can be made as to the extent and nature of a federal research program on buildings' systems controls and sensors. The large energy conservation potential and cross-cutting relationship of systems controls with other energy conservation technologies provide strong incentive to investigate this area further.

3.4 SELECTED BUILDINGS ENERGY CONSERVATION RESEARCH OPPORTUNITIES

Based on the preceding screening of the technologies in Table 3.5, five areas were singled out for additional analysis: Advanced Heat Pumps and Furnaces, Alternative Fuels Combustion, Thermal Storage Materials, Lighting Technology, and Integrated Appliances. The following subsections discuss each area's technical barriers, conservation potential and possible research opportunities.

3.4.1 Advanced Heat Pumps and Furnaces

Heat pumps offer the potential of substantial efficiency improvements over conventional space conditioning systems. However, considerable confusion arises when trying to describe efficiencies for space conditioning systems. One reason for the confusion is that remarkably little is known about their performance in actual operating environments, and literature in the area is replete with inconsistent information. Performance varies with the type of unit, its age, size, installation, position in the building, and many other variables. Another reason for the confusion is the inconsistency in the definition of efficiency. Until recently, the most common values quoted were the steady-state or maximum efficiency and the coefficient of performance (COP). Increasing interest in "true" efficiency has produced the energy efficiency rating (EER) and the seasonal performance factor (SPF), as well as the second-law efficiencies. To add to the confusion, each factor can be expressed in terms of primary or end-use fuel consumption as well as with or without parasitic losses included. Unfortunately, no matter which way the system performance is presented the number falls between about 0.5 and 3.0, which makes distinguishing among systems very difficult.

The efficiency measure that is most accurate and informative and increasingly being used is the SPF. The SPF is defined as the ratio of a) the sum of the useful heat delivered to and removed from the living space to b) the heat content of the fuel used over the entire year. The SPF is used here to compare various space conditioning systems.

The majority of heating in the U.S. is done with gas, oil, or electricity. Cooling is done almost entirely with electricity. Present gas and oil systems have SPFs that range from 0.45 to 0.65. Combining an oil or gas system with a typical high-efficiency air conditioner would yield a total system SPF of about 0.8 for Philadelphia or 1.5 for Houston. (Each climate will yield a different SPF; these two cities were chosen as representative of a cold and hot climate.) Present electric resistance heating systems have SPFs of nearly 1.0. Combining an electric resistance system with an electric air conditioning system mentioned above would give a total system SPF of about 1.2 for Philadelphia and 1.8 for Houston.

Hybrid systems, where gas or oil furnaces are used to provide extra support at low ambient temperature, use electric heat pumps for primary heating and cooling. They provide SPFs of about 1.8 for Houston and 1.3 for Philadelphia.

All electric heat pump systems provide the highest SPFs of available state-of-the-art systems with SPFs of 2.3 for Houston and 2.2 for Philadelphia. However, conversion losses at the generation plant reduce the overall efficiency of fossil fuel use by a factor of three. If electricity is generated using natural gas, the SPFs of electrical systems are logically reduced by this amount for comparison with natural gas systems. However, in the case of nuclear, coal, or hydroelectrical power, such a comparison is not so straightforward. These fuels could not conveniently be used to supply space heat as can natural gas. To avoid confusion, the SPFs presented here are defined only in terms of energy use at the consumer level. Electrical conversion losses are not included.

As shown in Table 3.1, space heating and cooling of buildings accounted for 15.5 quads. Implementing currently available heat pump equipment could reduce this by roughly one half. Additional existing conservation measures discussed in Section 3.1, such as insulation and weatherstripping, could further reduce space conditioning requirements by an additional 50%. Given these measures, the target energy flow for advanced space conditioning technologies is about four quads.

Advanced space conditioning systems include a variety of technologies. Advanced electric heat pumps, for example, can have multi-speed compressors, series or parallel compressors (to increase low-temperature capacity) or continuous capacity modulation, to name a few. Other technologies include gas-fired absorption cycles, free-piston Stirling-Rankine machines, V-type Stirling-Rankine machines, or Ericson-Ericson machines. Advanced furnaces such as the pulse-combination furnace or the heat pipe furnace also exist. These concepts are in varying stages of development. The highest potential exists for the electric heat pumps, which may have SPFs as high as 3.3 for Houston and 2.8 for Philadelphia. The pulse-combustion furnace combined with an electric central air conditioner has a SPF of 1.9 for Houston and 1.1 for Philadelphia. Of the all gas-fired units the V-type Stirling-Rankine had the highest SPF at 1.1 for Houston and 1.3 for Philadelphia. The SPF for these advanced systems is only an estimate and could definitely change under performance conditions. Most likely these numbers do not include parasitic losses. Meier (1979) indicates that the SPF of the Stirling engine heat pump is 1.25 for Philadelphia, excluding parasitic losses and only 0.95 with parasitic losses, compared to a SPF of 0.72 for a state-of-the-art gas furnace and electric air conditioner combination. This would yield only about a 25% reduction in energy consumption. Table 3.6 summarizes the SPFs for the above technologies. The maximum energy savings potential that could be attributed to advanced research is probably about 1.0 quad, assuming 100% market penetration. Realistically, the energy conservation potential of R&D is probably much less than this.

Because of the present large energy-savings potential of heat pumps and advanced furnaces, much R&D is currently being done by manufacturers and utility companies, such as the Gas Research Institute and the Electric Power Research Institute, and directed at the short term. Long-term R&D might address the following areas:

- frost formation and melting on heat exchangers

- refrigerants; alternatives to standard R-22, R-11, and R-12, with more diverse temperature ranges
- implementation of fully modulating motors
- novel heat exchanger designs.

This type of R&D would probably only directly affect the energy-use problem slightly but would impact things such as reliability and cost, which would influence the degree to which these technologies are used.

TABLE 3.6. Comparison of Seasonal Performance Factors (Meier 1979, and Gordian Associates 1978)

System	Houston	Philadelphia
Electric Heat Pump - Standard	2.0	1.9
Electric Heat Pump - High Efficiency	2.4	2.3
Hybrid - Electric Heat Pump with Oil or Gas Furnace	1.8	1.3
Gas or Oil Furnace with Central Air Conditioner		
without parasitic losses	1.5	0.77
with parasitic losses	--	0.72
Electric Furnace with Central Air Conditioner	1.8	1.2
Advanced Electric Heat Pump	3.3	2.8
Free-Piston Stirling-Rankine Gas Heat Pump	1.0	1.2
V-Type Stirling-Rankine Gas Heat Pump	1.1	1.3
Absorption Cycle Gas Heat Pump	0.6	0.9
Pulse Combustion Furnace with Central Air Conditioner	1.9	1.1
GE Stirling-Rankine Gas Heat Pump		
without parasitic losses	--	1.25
with parasitic losses	--	1.14

Much of the needed long-term research on advanced space conditioning systems is already being addressed in existing research programs. The Gas Research Institute has a funding level of $8 million in 1981 for residential space conditioning R&D (Gas Research Institute 1981). The Electric Power Research Institute has a funding level of $3.6 million in 1981 for their residential and commercial energy conservation research program (Electric Power Research Institute 1980). These research programs, as well as those in industry, should be examined carefully to determine where gaps in long-term R&D could be filled though federally sponsored research.

3.4.2 Alternate Fuels Combustion

Rising electricity prices and gas have spurred many homeowners to use alternate space heating fuels, such as wood and coal. In 1980 more than five million cords of wood were removed from national forests for noncommercial use. This figure represents a 25% increase from 1979 and a 10-fold increase from 1973. In addition, 25 million cords were removed for sale as a household heating fuel (Spokane Spokesman Review 1981). The trend in woodstoves between 1972 and 1978 is shown in Table 3.7. The 700% increase shows that wood heating has clearly become a significant space heating technology. Since many of the cast iron stoves are capable of burning coal and other solid fuels, in addition to wood, these fuels are future possible space heating sources.

TABLE 3.7. Domestically Produced and Imported Woodstoves (000s) (Booz, Allen and Hamilton, Inc. 1979)

Year	Domestically Produced	Imported Units
1972	140	20
1973	190	20
1974	240	80
1975	480	280
1976	470	200
1977	790	240
1978	770	380

The Office of Technology Assessment (OTA) (1980a) has estimated that biomass (wood and other plant material) could supply as much as 12 to 17 quads of energy per year by the year 2000. Of this, up to 10 quads could come from wood. If accurate, this level of resource availability would be sufficient to supply the majority of the space heating needs of the U.S. in the year 2000. Of course, regional imbalances in wood availability, transportation costs, and consumer preferences will almost certainly limit the contribution of biomass to less than 100% of space heating energy. However, biomass and other solid fuels have potentially enormous applicability to space heating.

Woodstoves are well developed as a technology. Design improvements are best left to individual manufacturers, although the woodstove has three problems that may offer areas of research opportunities: 1) particulate emissions, 2) indoor air quality in thermally tight houses, and 3) creosote problems. Because the woodstove industry is fragmented, private research efforts will probably not resolve these problems. Thus, federal research support should be considered.

Particulate problems with woodstoves arise because fuel is burned without emissions control. Many localities have experienced serious air-quality problems as a result of wood combustion and some have even banned woodstoves. Unless small-scale, inexpensive emissions control systems are developed, the amount of energy that can be obtained from woodstoves may be limited.

The indoor air quality problem arises because woodburning devices introduce particulate matter and trace metals into the living space (Moschandreas, Zabransky and Rector 1980). In well-sealed houses these pollutants may reach levels that pose health risks. Additional research is needed to determine the extent of the indoor air-quality problem that results from woodstoves. Design alterations in the stove or use of air-to-air heat exchangers to increase ventilation in thermally tight houses may alleviate the problem.

The third problem, creosote, is a resin-like substance that builds up on stove surfaces and chimney walls. High temperatures can ignite the creosote, causing dangerous chimney fires. Although some methods are known to minimize creosote buildup, such as avoidance of a cool chimney, no systematic base of knowledge about creosote exists. Further investigation of the processes involved in creosote buildup and means by which to control it is needed to resolve this serious impediment to woodstove use.

3.4.3 Thermal Storage Materials

Thermal storage is an important design element in solar heated and cooled buildings, naturally cooled buildings, and heavily insulated buildings. Thermal storage minimizes backup energy requirements by leveling large room temperature fluctuations normally occurring because of daily variations in sunshine and to a lesser extent, outdoor temperatures. Thermal storage can be obtained in construction materials (e.g., concrete, brick, stone, earth, and adobe) or in a separate storage tank(s) containing thermal storage materials (e.g., water salt ponds or rock). The optimum storage capacity depends upon many factors, including storage temperature effects on collector performance, thermal losses from storage, building insulation levels, and economics. For individual homes storage adequate for a few hours to a few days is most economical (Dean 1978). For community systems seasonal heat storage in underground tanks or reservoirs may be desirable.

Energy may be stored as sensible heat or latent heat (heat of fusion). Storge as sensible heat is well understood and reliable and can be regarded as a mature technology. Storage as heat of fusion, however, is not as well understood and has reduced storage volume as the only major advantage (Wyman et al. 1980).

In simple terms a building's potential for energy conservation can be analyzed by measuring its thermal performance with and without thermal storage. In practice the problem is complicated unless a specific building structure is assumed because variations in insulation, insolation, and buildings' inherent thermal mass markedly influence thermal storage's effectiveness. In new energy-efficient buildings added thermal storage might reduce energy requirements roughly 10 to 20%. If new buildings are assumed to account for half of the total housing stock, and buildings' energy use for space heat totals 4 quads per year in 2010 after implementation of other conservation measures, the total conservation potential for thermal storage materials is approximately 0.2 to 0.4 quads per year. Greater energy savings would be possible if passive solar retrofits of old buildings were used. Applied R&D would not significantly increase the energy conservation contribution of storage materials. However, improved storage materials that are more easily integrated into conventional structures may improve their acceptability in new house designs and application to retrofits.

Research opportunities for low-temperature thermal energy storage in buildings are possible because few basic barriers exist to its use. Some engineering development may be practical to improve heat conductivity and capacity of sensible heat storage materials. Latent heat storage materials have some basic problems, such as phase separation and supercooling, that offer potential areas of applied research (Dean 1978). One novel idea that warrants investigation is the use of thermal diodes. A thermal diode uses convective energy flows created by incident solar energy to circulate and store a heated fluid in a self-contained unit. A diode-like mechanism prevents reverse circulation from cooling the fluid at night. The heat radiating from the unit into the living space provides the space heating effect. Thermal diodes could be designed in a modular fashion to be integrated into building walls, which would keep costs low. Research into the heat transfer mechanisms and materials requirements is needed to make thermal diodes practical. All research efforts relating to storage materials should be coordinated with the DOE thermal storage research program and research programs in the International Energy Agency, the Commission of European Industries and private industry (Baylin 1979).

3.4.4 Lighting Technology

As shown in Table 3.1, total energy consumption for building lighting is approximately 3.3 quads per year. Most of the 1.0 quad consumed in the residential sector is used in incandescent bulbs. The commercial sector uses primarly fluorescent bulbs, with some incandescent, high-pressure sodium, and mercury vapor bulbs.

Table 3.8 shows the efficacies of various light sources in terms of lumens of light per watt of electrical input. This table shows incandescent bulbs to be very inefficient, emitting only 11 to 22 lumens per watt. The reason for the low emission is that most of the electrical energy is converted to infrared

TABLE 3.8. Energy Efficacies of Selected Artificial Light Sources and Theoretical Maxima (Dumas 1977)

Source	Approximate Lumens Per Watt
Incandescent	
40-watt general service	11.0
60-watt general service	14.3
100-watt general service	17.4
1,000-watt general service	22.0
100-watt extended service	14.8
Fluorescent	
two 24-inch cool white (approx. 20 watts each)	50
two 48-inch cool white (approx. 40 watts each)	67
two 96-inch cool white (approx. 112 watts each)	73
High-Intensity Discharge	
400-watt phosphor-coated mercury	46
1,000-watt phosphor-coated mercury	55
400-watt metal halide	75
1,000-watt metal halide	85
400-watt high-pressure sodium	100
Theoretical Maxima	
All input energy reradiated as pure white light only	200
All input energy reradiated as monochromatic light at 555 nanometers wavelength (peak sensitivity)	680

radiation, or heat, instead of radiation in the visible portion of the spectrum. Fluorescent bulbs are two to four times as efficient as incandescent bulbs, but still emit a great deal of radiation outside of the visible spectrum. The most efficient existing bulb is high-pressure sodium, with an efficacy of 100 lumens per watt.

Theoretically, energy could be converted to light at a rate of 680 lumens per watt at a wavelength of 555 nanometers. However, monochromatic light would not be suitable for human lighting purposes. Because the human eye is increasingly less sensitive to wavelengths above and below 555 nanometers, white light (uniform mix of all visible wavelengths) has a maximum theoretical conversion efficiency of 200 lumens per watt, or about twice that of the most advanced bulb available today.

Energy-use efficiency in lighting could be increased substantially. Most of the energy conservation potential could be achieved by applying existing technology and by reducing lighting levels. These improvements might reduce lighting energy by 50% by 2010. Further reductions through application of advanced technologies might reduce the remaining energy use in lighting by 10 to 20%, resulting in an energy savings of 0.16 to 0.33 quads per year.

Although long-term research may be able to result in bulbs with efficacies closer to the theoretical limit, this is probably not the optimal goal for lighting research. Many advanced bulbs, such as high-pressure sodium, simply do not have the aesthetic characteristics necessary for most applications. Lighting energy could be reduced by 50 to 75% in some applications by replacing incandescent bulbs with fluorescent bulbs. Fluorescent bulbs suitable for use in conventional lamps are already available on the market. Although they are still quite costly, they are cost effective on a life-cycle basis due to their efficiency and long life.

Some technology developments may offer research opportunities for improving lighting efficiency in common situations:

- high-frequency incandescent bulbs, 40-50 lumens/watt
- reflective coatings for incandescents, 30 lumens/watt
- solid-state ballasts, 18-25% energy use reduction in fluorescents
- lighting controls, automatic adjustments made to account for available daylighting
- task lighting
- high-frequency electrodeless lamp (e.g., Hollister lamp)
- xenon-filled incandescent bulb
- human factors, effects of various lighting levels and spectral mixes.

Determination of specific research activities should be coordinated with other research programs. In particular, the Illuminating Engineers Society sponsors long-term lighting research and through Lawrence Berkeley Laboratory DOE has programs examining the integration of artificial lighting with daylighting and various lighting technologies.

3.4.5 Integrated Appliances

In most buildings the various energy-using appliances operate in isolation from each other. In some cases they even oppose each other (e.g., lights and refrigerator contribute to the cooling load that must be handled by the air conditioner). However, because buildings generally contain a standard set of appliances, this need not be the case. Appliances could be designed for mutual or cascading energy use. Mutual energy use would involve using a single heat source to supply heat to more than one device (e.g., using a single combustor for space and water heating). Cascading energy use would involve using the waste heat from one device in another device (e.g., using heat from the refrigerator condensor coil to preheat water). Both options for integrating appliance energy use offer the potential to improve the overall energy-use efficiency in buildings.

Numerous configurations could integrate the space heater, water heater, air conditioner, refrigerator, freezer, and range in residential and commercial buildings. A study by A. D. Little, Inc. (1977) examined 342 combinations in which waste heat from one device could be used in another and an additional 7 combinations in which a single heat source could be used for two different devices. This study used a computer model to evaluate the maximum potential energy savings possible by 1990 and with each combination. Ninety-seven of the 349 concepts were estimated to have the potential to save over 0.01 quad per year. Using other criteria, such as engineering feasibility and economic potential, these 97 were narrowed down to the six most promising integrated appliance options:

- using heat from the air conditioner to preheat water
- combining the furnace and water heater
- using waste heat from a commercial range to heat water
- using waste heat from the refrigerator to heat water

- recovering heat from residential drain water
- recovering heat from commercial drain water.

The first three options were considered the most promising. Table 3.9 summarizes the energy conservation potential for these three technologies. These energy conservation estimates are based on the projected appliance efficiencies for 1990, shown in Table 3.10. These assumed appliance efficiencies have a direct impact on the conservation potential of the various integrated appliance schemes. For example, if the efficiency of the air conditioner is improved, or the space cooling load is reduced, then the air conditioner will generate less waste heat for heating water. Despite the conservative assumption of significant improvements in appliance efficiency by 1990, the A. D. Little, Inc. study (1977) projects substantial energy savings for the three integrated appliance options in Table 3.9. The combined Central Air/Water Heater and Furnace/Water Heater are capable of saving 0.3 and 1.1 quads per year, respectively, in 1990. Because the previously discussed scenario for buildings energy use did not show substantial change in buildings energy-use patterns between 1990 and 2010, these energy-savings estimates are assumed to

TABLE 3.9. Potential Energy Savings from Various Integrated Appliance Configurations (A. D. Little, Inc. 1977)

Integrated Technology	Annual Energy Savings for Unit (10^6 Btu)	Added First Cost Installed (1975 $)	Years to Payback	Maximum 1990 Inventory (10^3 Units)	Max. Annual Energy Savings in 1990 (10^{15} Btu)
Central Air/ Water Heater	28.8	300	3.5	10,600	0.3
Furnace/ Water Heater	34.3	124	1.0	32,600	1.1
Electric Range/ Water Heater					
Small	224	1,700	2.5	84	0.02
Large	3,000	5,330	0.6	4	0.01

TABLE 3.10. Estimates of Residential Appliance Efficiency to 1990 (at point of use) (A. D. Little, Inc. 1977)

Appliance	Annual Consumption Per Unit (10^6 Btu/Year) For 1972	For 1990	Other Estimates of Percent Reduction ORNL	ADL-CEQ/FEA	Percent Reduction Used In This Study
Water Heater					
gas	37.2	27.2(24)[a]	35	25	27(35)[a]
electric	21.9	18.4(17)[a]	14	20	16(22)[a]
Dishwasher (Auto)					
gas	7.8	6.2	NE[b]	22	20
electric	4.6	3.6	NE	22	20
Dishwater (Man)					
gas	7.8	7.8	NE	NE	0
electric	4.6	4.6	NE	NE	0
Clothes Washer					
gas	7.8	6.2	NE	10	20
electric	4.6	3.6	NE	10	20
Bath/Shower					
gas	21.6	21.6	NE	0	0
electric	12.7	12.7	0	0	0
Refrigerator	5.6	3.6	42	40	35
Range/Oven					
gas	13.8	7.2	42	26	48[c]
electric	4.09	3.0	14	25	26[c]
Clothes Dryer					
gas	8.2	6.5	NE	10	20
electric	4.3	3.9	NE	10	8
Air Conditioning[d]					
central	13.9	10.4	28	40	25
room	4.4	3.3	28	NE	25
Space Heating					
gas	120.0	90.0	35	50	25
electric	46.0	23.0	15	45	50[e]

(a) Includes an 8% reduction in water usage.
(b) No estimate.
(c) Includes 50% of ovens replaced by microwave.
(d) Includes improved insulation.
(e) Heat pump.

be able to be used as approximations of the annual energy savings in the year 2010. The Commercial Range/Water Heater option offers smaller potential energy savings, but has a very attractive payback period of 0.6 years for large installations.

Although integrated appliances are a very attractive energy conservation idea, not all options need applied research. For example, a product that allows use of waste heat from an air conditioner to heat water is already on the market. Engineering development should be sufficient to bring many of these ideas to market. However, some research to support this promising concept may be warranted and should be considered. The following are example research ideas:

- more effective low-cost heat exchangers
- improved sensors and controls to optimize operation of systems
- investigation of a completely automated, centrally located appliance system designed to combine and optimize total energy use in a building.

4.0 TRANSPORTATION

In 1978 the transportation sector accounted for 20.5 quads of total energy use or slightly over one quarter of the gross energy consumption in the United States (Oak Ridge National Laboratory 1980). Although transportation uses less total energy than the buildings and industry sectors, it represents 50% of national oil consumption. Because of the rapidly rising oil prices and the political instability of oil-producing nations, the transportation sector is extremely important from an energy conservation standpoint.

Table 4.1 shows a rough breakdown of energy use in the transportation sector by end-use and fuel type. Roughly 97% of energy use in the transportation sector is petroleum based. Automobiles and trucks account for about 75% of the total energy used and virtually all of that comes from petroleum. The largest specific fuel uses are gasoline and distillate fuel oil in automobiles and trucks and jet fuel in aircraft. These end uses offer promising energy conservation targets.

The automobile alone accounts for the following energy consumption percentages (National Academy of Science 1979):

- 28% of total U.S. petroleum consumption;
- 58% of the petroleum consumed for passenger and freight transportation;
- 13% of personal consumption expenditures, exceeded only by food and housing;
- 13% of all the energy consumed in 1975, up from 9% in 1950.

Because of its enormous impact on the national energy economy, this conservation analysis focuses on the automobile. Some of the technologies discussed in the context of automobiles may apply to trucks, but they are not specifically considered as truck technologies. Focusing on automobile energy conservation technologies enables more thorough coverage of this important area than would be possible if the analysis were extended to include the rest of the transportation sector. The nonautomobile areas certainly offer potential energy conservation research opportunities and should be investigated further, but are beyond the scope of this study.

TABLE 4.1. Energy Use in the Transportation Sector, 1978 (10^{15} Btu)[a] (Arthur D. Little, Inc. 1977)

End Use	Fuel Type							
	Gasoline	Distillate Fuel Oil	Liquified Gases	Jet Fuel	Residual Fuel Oil	Natural Gas	Electricity	Total
Automobiles	10.4	---	---	---	---	---	---	10.4
Trucks	3.7	1.3	0.1	---	---	---	---	5.1
Aircraft	0.2	---	---	1.7	---	---	---	1.9
Marine	0.2	0.3	---	---	1.0	---	---	1.5
Pipeline	---	---	---	---	---	0.6	0.06	0.7
Rail	---	0.6	---	---	---	---	0.01	0.6
Other	0.2	0.2	---	---	---	---	---	0.3
Total	14.7	2.5	0.1	1.7	1.0	0.6	0.06	20.5

(a) Entries may not add to totals due to independent rounding.

4.1 TRANSPORTATION ENERGY CONSERVATION POTENTIAL

To evaluate applied research's potential contribution to energy conservation in automobiles, probable future energy use in automobiles without technological advances should be examined. The Committee on Nuclear and Alternative Energy Systems (CONAES) study made a range of automobile energy-use projections in the year 2010 (National Academy of Science 1979). These projections were made assuming no technological breakthroughs. The primary energy-use determinant in automobiles was assumed to be price. The following are other assumptions affecting the CONAES projections:

- The technological limit on fuel economy will be a fleet average of 37 mpg.
- Fuel economy will not meet the federal standards of 27.5 mpg by 1985, unless economic conditions cause it to do so.
- New car fuel economy will increase linearly to its maximum level by 2000 and remain constant thereafter.
- The load factor (persons per vehicle) will vary only slightly with fuel price (i.e., no massive shifts to carpooling).
- Ten percent of the automobile fleet will be replaced each year, causing a lag between average new car fuel economy and fleet average economy of approximately 10 years.

Using these assumptions, CONAES projected automobile energy use for the four future energy scenarios described in Chapter 3. Scenarios A and B represent increasing real energy prices; Scenario C represents roughly constant energy prices; and Scenario D represents declining energy prices.

Table 4.2 shows the results of these four CONAES projections of automobile energy use. All four scenarios show increases in travel demand. However, at the levels of travel shown for scenarios C and D, demand is probably reaching a saturation point. Increased travel above these levels would be expected to shift to other modes, such as air travel.

The most striking difference among the four scenarios is the effect of energy prices on the degree to which new vehicle fuel economy approaches the

TABLE 4.2. Scenarios of Automobile Annual Expenditures, Operating Costs, Travel Demand, and Energy Use in 2010 (National Academy of Science 1979)

	1975	Scenario A	Scenario B	Scenario C	Scenario D
Total Expenditure (1975 $/capita)	830	1170	1170	1170	1170
Gasoline Price Without Tax (1975 $/gal)	0.45	2.18	1.09	0.45	0.27
Total Gasoline Price with Tax (1975 $/gal)	0.57	2.58	1.37	0.67	0.47
New Vehicle Fuel Economy (mpg)	14	37	26	20	18
Total Operating Cost (1975 $/vehicle-mile)	17.3	21.9	19.1	16.6	15.7
Load Factor (passengers/mile)	2.2	2.4	2.3	2.2	2.1
Travel Demand (passenger-mi/capita)	10500	12800	14100	15500	15700
Time in Autos[a] (min/day per capita)	53	65	71	78	79
Energy Use Per[b] Capita (millions Btu)	42.6	18.1	29.2	44.0	51.3
Energy Consumption (10^{15} Btu)	9.1	5.0	8.1	12.3	14.3

(a) Based on an average speed of 32.6 mph.

(b) $\text{Btu/capita} = \frac{\text{(passenger-miles/capita)(125,000 Btu/gal)}}{\text{(load factor)(fuel economy, mpg)}}$

technological limit of 37 mpg. In scenario A, the limit is achieved, but in all the other scenarios fuel economy falls well short of the technological maximum. If the CONAES calculations are correct, this situation would indicate that unless energy prices rise substantially, technological improvements will not play a significant role in promoting energy conservation in automobiles. Without higher energy prices (or binding federal regulations) the economically appropriate level of fuel economy can readily be achieved with existing technology.

If future energy prices are sufficiently high, either in reality or as a reflection of the noneconomic risks associated with oil imports, technological improvements in the automobile could play a valuable role in future energy conservation efforts. For this reason, the degree to which improved technology could reduce the amount of energy used by automobiles should be determined. Using CONAES estimated 37 mpg as the highest fleet-average economy without technological improvement, annual automobile energy consumption can be projected to fall to approximately 5 quads per year. One author estimates that automobile fuel consumption can be reduced by up to 67% through technological improvements (Grey, Sutton and Zlotnick 1978). Another projects that fuel economy levels of 82 to 113 mpg are possible by 1995 (Gray and Von Hippel 1981). If these improvements could be achieved on a fleetwide basis, automobile energy consumption could be reduced by about two quads per year below the lowest CONAES projection. Not only is this a sizeable energy savings, but the savings would be in the form of oil. Based on this brief analysis, applied research into automotive technology has very attractive potential payoffs.

4.2 IDENTIFICATION OF TRANSPORTATION CONSERVATION TECHNOLOGIES

Following the methodology outlined in Figure 2.1, transportation energy conservation technologies that address the major energy end uses were identified. Because autos and trucks account for over 75% of the energy used in the transportation sector, automobile and truck technologies were emphasized. However, because other energy uses in the transportation sector may offer promising energy conservation research targets, they were included in the energy conservation technology identification process, but they were not subjected to detailed analysis.

To facilitate the identification of automobile and truck energy conservation technologies, current energy use by these vehicles was examined in detail. Figure 4.1 gives a breakdown of energy use in an automobile during the standard driving cycle used by the Environmental Protection Agency (EPA) to test vehicles' fuel economy. This diagram shows four levels of energy losses in a typical passenger vehicle: Level 1 losses are due to exhaust and cylinder cooling and account for 62% of total losses; Level 2 losses are due to friction and air pumping and account for an additional 13% of total losses; Level 3 losses are due to accessories, transmission, axle, braking, coasting, and idling and account for 13% of total losses; Level 4 losses dissipate the remaining 12% of the original energy in the fuel into tire and air resistance losses. Because each of the losses in Figure 4.1 could be reduced through engine and vehicle redesign, this figure provides a valuable checklist to consider in identifying technologies to reduce energy losses in automobile engines.

Table 4.3 summarizes a general list of transportation energy conservation technologies. This list is not all inclusive, but it does contain the major technology areas where applied research holds potential for reducing transportation energy consumption. These areas include alternative engines and other vehicle improvements. The ideas for the other transportation subsectors include incremental technology improvements, as well as alternative technologies for performing desired tasks.

4.3 SCREENING OF TRANSPORTATION CONSERVATION TECHNOLOGIES

Table 4.3 shows a range of energy conservation technologies relating to the transportation sector. Because of the importance of automotive technologies, these technologies were examined for research opportunities. Technologies addressing the nonautomotive subsectors of the transportation sector were included in Table 4.3 to indicate types of possible energy conservation measures. Some of these conservation technologies may prove to be fruitful areas for applied research and should therefore be examined in future studies. However, they were not considered further in this study.

After the scope of the analysis was reduced to automotive technologies, the methodology outlined in Figure 2.1 required that a screening process be

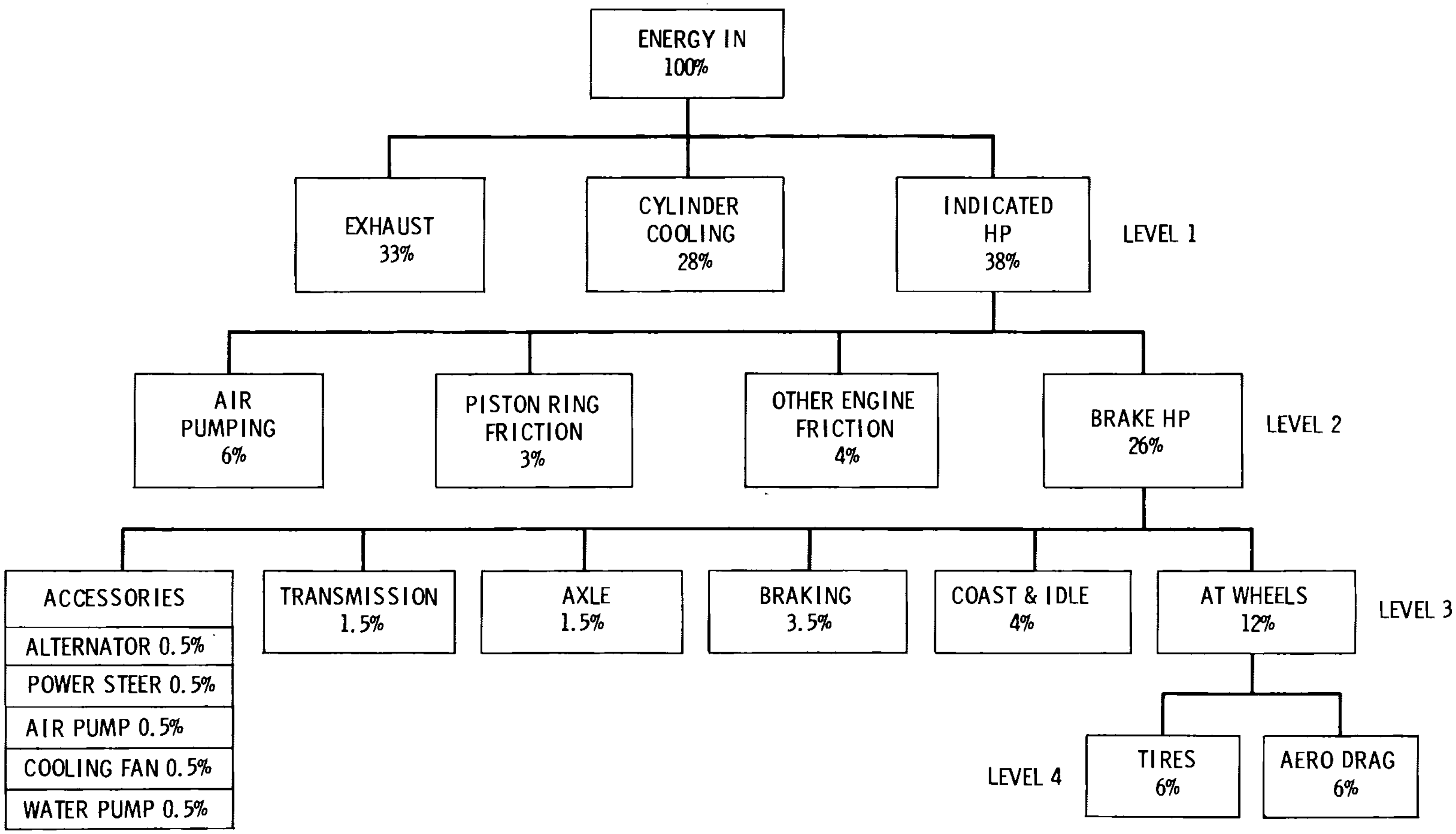

FIGURE 4.1. Energy Use in Passenger Car During EPA Cycle

TABLE 4.3. Transportation Energy Conservation Technologies

Automobiles and Trucks

- Stratified Charge Engines
- Dilute Homogenous Charge Engines
- Improved Diesels
- Adiabatic Diesels
- Stirling Engines
- Rankine Engines
- Brayton Engines
- Hydrogen-Fueled Engines
- Free-Piston Engines
- Adkinson Engines
- Bourke Engine
- Still Engine
- Improved Otto Cycle Engines
- Turbochargers and Superchargers
- Hybrid Vehicles
- Electric Cars
- Regenerative Braking
- Increased Auxiliaries Efficiency
- Improved Transmissions
- Friction Reduction (Tribology)
- Reduced Rolling Resistance
- Vehicle Weight Reduction
- Reduced Aerodynamic Drag
- Alternate Fuels Combustion
- Fuel Catalysts
- Computer Controls

Aircraft

- Weight Reduction
- Laminar Flow Control
- Hydrogen Engines
- Improved Propeller (Turboprop)
- Continuous Flight Systems
- Sissor Wing and Swing Wing
- Increased Engine Efficiency
- Improved Turbulent Performance
- Flying Wings

Marine

- Efficient Reduction Gears
- Advanced Engine Concepts
- Hull Drag Reduction
- Computer Navigation
- Weight Reduction
- Low-Quality Fuel Combustion
- Hovercraft
- Propeller Design
- Ducted Fans
- Reduced Repair and Maintenance

Pipelines

- Improved Slurries
- Pipeline Container Transport
- Fluidized Bed Pipelines
- High-Efficiency Pumps
- LNG/Cold Weather Pipelines
- Drag Reducing Coatings/Additives

Rail

- Regenerative Braking
- Reduced Drag
- Improved Rails
- Broad-Gauge High-Speed Corridors
- Lightweight Cars
- Improved Bearings
- Levitation Techniques
- Sway Reduction
- Advanced Coal Burners
- Advanced Steam Engines
- Photovoltaic Power Supply

Other

- Substitution of Communications for Travel
- Low-Energy Water Pumping (Humphrey Pump)

applied to these technologies. As mentioned in Chapter 3, this screening is based on two criteria: 1 Does the technology offer significant energy conservation potential? and 2) Would applied research play an important role in realizing the potential energy savings of the technology?

Because automobiles use 10.4 quads of energy annually (see Table 4.1), even a 1% efficiency improvement would result in an estimated 0.1 quad savings per year. Since virtually all automobile energy use is petroleum based, this savings translates into 17 million barrels of oil per year. The CONAES scenarios for the year 2010 show automobile energy consumption between 5.0 and 14.3 quads per year. Clearly, automobiles are and will continue to be an important area for energy conservation.

Taken individually, several automotive technologies offer significant energy savings. However, the energy savings from individual technologies are not always additive. For example, two alternative automobile engines cannot both simultaneously achieve their maximum conservation potential because both cannot totally penetrate the market. Thus, as the number of technologies under development increases, the expected energy conservation payoff from each technology decreases. Although a range of technology options should be kept open through a diverse research effort, overinvestment of research into competing technologies should be avoided.

To avoid overemphasizing research into competing technologies in the screening processes, the second criterion, the role of applied research, must be emphasized. Screening the technologies according to the potential role of applied research involves consideration of the technology's technical merits, as well as the potential nontechnical barriers to the technology's application. Both technical and nontechnical issues can affect the impact of the energy conservation payoff from a particular research project. The automotive technologies were screened according to both energy conservation potential and the role for applied research. The screening of the technologies is discussed below in the order that they are listed in Table 4.3. This screening process allows selection of technologies that can be justifiably argued to be potentially attractive research targets for further analysis.

Stratified charge engines use a spatial variation in air/fuel ratio to facilitate combustion of an overall lean air/fuel mixture. An increase in thermal efficiency over conventional Otto-Cycle engines results. The characteristics of stratified charge engines appear to be compatible with automobile requirements and therefore give this engine a reasonable chance for commercialization. Stratified engines are discussed in further detail in Section 4.4.1.

Dilute homogeneous charge engines rely on the dilution of the air/fuel mixture with a nonreacting gas, such as excess air, exhaust gas, or possibly a noble gas, to lower the combustion temperature. Some research results have indicated slight fuel economy improvements, although theoretical thermodynamics predict that the opposite should occur. The primary advantage of charge dilution appears to be that it would suppress the formation of NO_x. Because dilute homogeneous charge engines do not have a clear energy conservation potential, they are not considered further in this study.

The diesel engine has already demonstrated the ability to substantially improve automobile fuel efficiency. Further research and development on this promising engine are discussed in Section 4.4.2.

One particularly interesting potential development in diesels is the adiabatic diesel, which offers even greater efficiency than conventional diesels. The adiabatic diesel is discussed separately in Section 4.4.3.

The Stirling engine has the potential for high fuel economy, low emissions, and use of alternative fuels. Its low-speed torque characteristics are well-suited to automobile use. However, important barriers to practical application of Stirlings still exist. Research opportunities relating to Stirling engines are discussed in Section 4.4.4.

Rankine engines appear to offer little or no significant fuel efficiency advantages over conventional Otto-Cycle engines. In addition, inherent startup delay problems may make this engine unacceptable to consumers. Because this technology lacks clear justification as an energy conservation possibility, it is not discussed further in this study.

Brayton engines, commonly referred to as automotive gas turbines, have the potential for long life with low maintenance, good low-speed torque characteristics, and high power-to-weight ratios. With certain key technological developments they may also offer increased fuel efficiency over Otto engines. Specific areas requiring research on Brayton engines are discussed in Section 4.4.5.

Hydrogen-fueled engines would have excellent emissions characteristics, producing water vapor as their primary product of combustion. However, because hydrogen permeates most metals and is a gas at common temperatures, it is very difficult to store for fuel use. Also, hydrogen production through electrolysis is extremely expensive. Without massive electrification of the U.S. economy, hydrogen is not likely to become available as a widespread fuel. Unless a reasonable case can be made for a hydrogen economy in other than the very long term, substantial research support of hydrogen-fueled engines is not justified. They are therefore not examined in this study.

Free-piston, Adkinson, Bourke, and Still engines are older engine concepts that were developed technically but were never applied commercially. Given the heightened interest in vehicle fuel economy, these engines may warrant consideration as alternative vehicle power plants to the conventional Otto and diesel engines.

A free-piston engine is usually powered by an opposed-piston (inherently vibrationless), two-stroke diesel engine, each power piston being directly connected to a compressor piston. The power output of the engine section is absorbed by the compressor section (Marks 1967b). Thermal efficiencies of 50% are claimed possible, as opposed to 33% for Otto cycles and 40% for diesels (Norbye 1980).

The Adkinson cycle engine uses an unequal stroke length for the intake-compression and expansion-exhaust phases of a four-stroke cycle. The concept is to expand the burnt fuel charge to atmospheric pressure, which requires the expansion stroke to be longer than the compression stroke. In the early 1890s, when the engine was developed, this required a complex mechanical linkage. An Adkinson engine is attractive because, based on a thermodynamic analysis and depending on several factors it could theoretically produce a 40% fuel savings compared to an Otto cycle, thereby raising overall efficiency above that of current diesel engines.

The Bourke engine is a two-stroke engine that uses a scotch-yoke linkage to connect the pistons to the crank and a closed chamber under the piston, rather than the crankcase to compress the scavenge charge. This creates the basis for a practical adiabatic engine. To avoid the lubrication and wear problems that plague the adiabatic diesel, the Bourke's scotch yoke can be combined with ringless "labyrinth" piston seals in which no part of the piston touches the cylinder walls. The high thermal efficiencies of adiabatic engines make the Bourke a potentially attractive engine candidate.

The Still engine generates steam directly in a water jacket surrounding the combustion cylinder in an internal combustion engine. The power developed by the steam is 20 to 30% of the combustion engine's power, and consequently, both the engine's power and efficiency are increased by this amount. A brake thermal efficiency of 40% from one-quarter to full load was obtained under test of a 300 horsepower engine in 1919 (Marks 1967a).

The lack of easily accessible data puts a thorough evaluation of the free-piston, Adkinson, Bourke, Still and other novel engine concepts outside this study's scope. However, the attractive technical features of these concepts call for further consideration. A study of novel engine concepts would be a fairly low-cost option for the government to pursue and would offer the possibility of discovering a promising research area outside the mainstream of energy conservation research.

The standard Otto-Cycle engine is a well-known, commonplace technology. However, many possible modifications, such as fuel preheating, fuel vaporization, improved carburetors turbochargers, superchargers, and improved emissions controls, still could increase fuel economy. Because of the ease with which these modifications could potentially penetrate the market, improved Otto-Cycle engines are examined in more detail in Section 4.4.6.

Electric and hybrid cars use batteries to supply all or part of their power. Aside from the impact of electrically-powered automobiles on the need for electrification, these vehicles have been plagued with technical problems. Batteries are currently heavy, expensive, and short-lived. Also, all-electric cars are very limited in both power and range. Hybrid vehicles, which combine an electric motor with a fuel-powered engine, have better characteristics. However, the most optimistic results indicate that hybrid vehicles have the potential for 40% fuel economy improvements over conventional vehicles during a typical driving cycle. This degree of fuel efficiency improvement does not offer a significant advantage over the potential for advanced diesels and Stirling engines. In addition, hybrid vehicles will almost certainly be more expensive than other automotive power plants, because of their increased complexity. Widespread use of batteries in automobiles could also have a severe impact on critical materials, such as lead, nickel, and zinc. An appropriate government role, which is currently being covered by DOE, is the development of advanced battery concepts. Development and design work on electric and hybrid vehicles is being done by the automakers. Deciding which options to pursue is best left to the industry. Although the federal government may have some research opportunities in the form of support activities, electric and hybrid are surrounded by sufficient uncertainties to cast at least some doubt on their promise. Therefore, they are not considered further in this study.

Regenerative braking is used to recover energy that is normally lost during braking. One type of regenerative braking is to use a generator to convert braking energy into electrical energy to recharge the batteries of an electric vehicle. Mechanical regenerative braking, which stores the kinetic energy dissipated during braking in a flywheel, could be used with any vehicle. One source estimates that regenerative braking combined with a continuously variable transmission (CVT) could reduce automobile energy consumption by 35% (the CVT accounts for 20% of the increase) (Grey, Sutton and Zlotnick 1978). However, the potential complexity of flywheel systems might inhibit their commercial viability. More work needs to be done to assess the practicality of regenerative braking, and because electric vehicles are not being considered in this study, this technology is not examined further.

As shown in Figure 4.1, auxiliaries, such as the alternator, power steering, air and water pump, and cooling fan, account for 2.5% of total automobile energy use, or 10% of brake horsepower. Improved efficiencies in these auxiliaries could reduce engine load and thereby improve fuel efficiency. However, accessory design is the function of the automakers. Since the benefits from improved auxiliary design would be captured by the automakers, this would not seem to be an appropriate area for government research. Auxiliaries are therefore not considered in this study.

As shown in Figure 4.1, transmissions account for 1.5% of total energy losses in an automobile or 4% of indicated engine horsepower. Reducing these losses could improve automobile fuel efficiency. Improved transmissions also offer the potential for allowing the engine to operate in its most efficient range despite varying loads and speeds. One source estimates that a continuously variable transmission matched with a conventional engine could improve fuel efficiency by 20% (Grey, Sutton and Zlotnick 1978). Since improved transmissions could presumably be matched to almost any type of engine, this automotive technology improvement appears attractive. Research opportunities relating to improved transmissions are discussed in Section 4.4.7.

Figure 4.1 shows engine friction to account for 7% of total automobile energy losses, or about 18% of indicated horsepower. Other friction losses occur in the transmission, axle, and wheel bearings. Reducing this friction through improved lubricants and materials could directly improve automotive fuel efficiency. Advances in lubrication and materials, which fall under the science of tribology, are also critical components in the development of a continuously variable transmission. Because of its broad application to automotive fuel efficiency, friction reduction (and tribology in general) is considered further in Section 4.4.8.

Rolling resistance, as shown by Figure 4.1, accounts for 6% of total energy use in automobiles or about 16% of indicated horsepower. Introduction of radial tires has resulted in significant fuel economy improvements through reduction in rolling resistance. Further improvements in tires and suspension systems could achieve additional energy savings. Because this technology could be applied to virtually any type of road vehicle, research opportunities in reduced rolling resistance are examined in Section 4.4.9.

The fuel economy of vehicles is directly proportional to weight. A 20% vehicle weight reduction combined with a 20% engine size and power reduction would leave acceleration and hill climbing unchanged, while reducing fuel consumption by 20% (Wolfe 1975). These fuel economy improvements from weight reduction applies to all vehicles, regardless of engine type. Research opportunities relating to weight reduction are discussed in Section 4.4.10.

Aerodynamic drag, as shown by Figure 4.1, accounts for 6% of total automotive energy use, or about 16% of indicated horsepower. A "typical" auto has an aerodynamic drag coefficient of around 0.55. A lower limit for this coefficient is probably near 0.3 to 0.35, although very streamlined designs could reduce the drag coefficient below this (Wolfe 1975). Government research into aerodynamic modeling and measurement techniques might be an appropriate form of support in this area. However, streamlining is so intimately a part of overall vehicle design that specific designs must come from private manufacturers. Thus, individual R&D opportunities pertaining to reduction of aerodynamic drag are not addressed in this study.

Use of alternate fuels to replace petroleum is virtually certain to become a reality for automobiles in the next century. To smooth the transition to these fuels, an adequate alternate fuel information base concerning the properties and compatibility with engines is essential. Areas in which opportunities for research could facilitate alternate fuel use are examined in Section 4.4.11.

Fuel catalysts are vehicle fuel additives that improve combustion efficiency. Empirically developed fuel catalysts that reputedly produce slight power and fuel economy increases in gasoline engines are already on the market. However, if a catalyst results in a higher combustion temperature, increased NO_x production would occur. Fuel catalysts that produce longer and more complete combustion at lower temperatures could improve fuel economy and reduce NO_x emissions and could be a potential research target. Another fuel catalyst possibility would be development of a fuel additive or combustion chamber coating that would reduce soot production in diesels. Fundamental research into catalysts' combustion process and mechanisms could help facilitate systematic identification of fuel catalysts. Although this may present a promising research area, fuel catalysts are not discussed further in this study because of a lack of data.

Computer controls appear to be the future way to improve automotive performance and efficiency. All the major auto manufacturers are investigating the use of on-board microprocessors for control of transmissions, cooling systems, fuel injection systems, and auxiliaries. Products are already on the market to provide real-time fuel efficiency data. To promote improved controls development, development of sensors to allow internal combustion measurements for closed-loop real-time engine control and optimization appears necessary (Rabbins et al. 1980a). However, most development of control systems must be an integral part of engine and vehicle design, and as such, is in the purview of the auto manufacturers. Therefore, automotive computer controls are not discussed further in this study.

4.4 SELECTED AUTOMOTIVE RESEARCH OPPORTUNITIES

The following discussions examine the energy conservation potential, major research opportunities, existing research programs, and nontechnical barriers relating to the automotive technologies that were selected above for further analysis.

4.4.1 Direct Injection Stratified Charge Engines

Charge stratification is a concept in which a spatial variation in air/fuel ratio is established in the cylinders of an internal combustion engine. The charge varies from rich near the spark plug electrode to very lean at the edges of the combustion volume, for an overall lean air/fuel ratio in the cylinder. One way to achieve charge stratification is to use a prechamber with a separate fuel system. In this configuration a rich mixture is admitted to the prechamber and ignited by a spark plug. The hot combustion gases pass out through a channel into the main cylinder where they ignite a very lean mixture. This type of stratified charge engine has been the focus of research since the 1920s and is currently offered commercially in Honda's Compound Vortex Controlled Combustion (CVCC) engine.

A second method of achieving charge stratification, and the subject of this section, is called the direct injection stratified charge (DISC) engine. In this concept no prechamber is used. The fuel and air are introduced directly into the cylinder so that the fuel concentration is much higher near the spark plug. Normally this is accomplished by first admitting an air charge with a swirling motion and then injecting the required amount of fuel.

The DISC engine has several advantages over regular Otto-Cycle engines and also over prechamber stratified charge models. Compared to Otto-Cycle engines, the DISC engine has increased thermal efficiency due to overall lean conditions. The air charge is normally unthrottled, leading to further efficiency increases. Late fuel injection reduces the potential for knock, allows high compression ratios, and reduces or eliminates octane requirements. Positive ignition with spark plugs produces good cold start and warmup capabilities. Direct fuel injection provides rapid engine response, contributing to low emissions during transient conditions.

The DISC engine also offers advantages over prechamber stratification, which poses several troublesome characteristics: two chambers raise the surface to volume ratio, increasing heat losses; the incoming charge must be throttled to adapt to part-load conditions; and finally, the connecting orifice must be small to permit charge stratification, yet large to promote rapid mixing.

Theoretically, the DISC engine should have excellent emission characteristics due to overall lean combustion. However, in practice this is difficult to achieve. Hydrocarbon emissions are low due to the lean conditions. Low carbon monoxide emissions require rapid mixing after ignition, in contrast to the initial slow mixing. Control of nitrous oxides can lead to extensive fuel economy penalties. In general, currently regulated emissions (HC, CO, and NO_x) are fairly good, but will require standard emissions controls to meet future, more stringent standards. Particulate emissions and odor may be as high as in diesel engines.

As shown in Table 4.1, highway vehicles currently consume about 15 quads of energy per year, roughly 10 quads for automobiles and 5 quads for trucks. The CONAES scenarios discussed in Section 4.1 project automotive energy use in the year 2010 to be between 5.0 and 14.3 quads, using existing technology. An early prediction estimated the fuel economy advantage of the DISC engine over a current Otto cycle as 3 to 6% in combined urban and highway driving (Jet Propulsion Laboratory 1975). A more recent study predicted a combined driving advantage of 15%.[a] Despite these relatively modest predictions of improvement, one vehicle testing program comparing gasoline and DISC engines in delivery trucks demonstrated improvements from 20% for highway driving to 31%

(a) Dowdy, M. W. 1982. "Advanced Automotive Heat Engines." Handbook of Energy Technology and Economics. John Wiley & Sons, New York, New York (to be published in 1982).

for urban driving[a]. When the test data are weighted more heavily, a reasonable improvement figure for combined urban-highway driving is assumed to be 20%. DISC engines could be used in all automobiles and in gasoline-burning trucks, which are shown in Table 4.1 to account for about three fourths of truck energy consumption. If full market penetration for automobiles and Otto-engine trucks is assumed, the ultimate conservation potential of the DISC engine is approximately 2.7 quads per year at current consumption.

Several private sources are close to commercialization decisions on the DISC engine. This engine could be introduced in the 1985 to 1990 period with full market penetration occurring within ten years.

The DISC engine is a relatively well-developed concept. Most of the necessary work required to perfect this technology can be accurately described as development rather than research. Three areas of applicable technology development are commonly identified:

1. Fuel injection systems - Further development of the fuel injection system will be required to optimize fuel consumption and emissions and reduce cost.
2. Emissions - Emissions from DISC engines require further characterization. Cycle operating characteristics must be optimized and emission controls must be integrated with the engine.
3. Combustion - Fundamental research into combustion phenomena can provide insights into the complex behavior of stratified charge engines. A more basic understanding of the processes can supplement applied engine research and facilitate the development of engine hardware optimized for fuel economy and emissions.

These three R&D activities are strongly interrelated. All are necessary to the success of the DISC concept, although the first, fuel injection systems, is most often cited as the critical need of the DISC program.

(a) Argonne National Laboratory. 1981. Federal Sponsored Stirling Engine Related Concepts, Period 1975 to 1981 (Draft).

Development of direct injection stratified charge engines has been pursued in recent years by Ford, Texaco, and Mitsubishi. The following is a summary of the Ford and Texaco efforts:

- The Ford PROCO engine (PROgrammed COmbustion) is very near a spark-ignition engine. Injection occurs early in the cycle and is completed before ignition. This practice permits preignition vaporization and mixing, allowing good use of the air supply and maximizing power output. It also establishes a potential for knock so the compression ratio is kept moderate (11:1) and fuel requirements are somewhat demanding (80 octane rating). Two spark plugs are used to increase the tolerance for exhaust gas recirculation. Originally unthrottled, the engine was later changed to moderately throttled operation to meet unburned hydrocarbon emission standards at part-load and idle. A couple of years ago Ford announced that the PROCO engine was close to commercialization and could be mass produced in the last half of the 1980s. More recently Ford has abandoned the PROCO program. Reasons include manufacturing and cost problems with the precise fuel injection system[a] and a desire to concentrate on the diesel (Argonne National Laboratory 1981).

- Texaco is developing its own DISC concept, TCCS (Texaco Controlled Combustion System). This engine, unlike PROCO, is close to a diesel engine. A normally unthrottled air charge is introduced with a swirl. Fuel is injected with a swirl in the same direction and ignited. Injection continues after ignition. Late injection and positive ignition eliminate both octane and cetane requirements and the engine can run with any distillate fuel. Late injection also hinders mixing, resulting in lower power and higher particulate emissions than the PROCO.

(a) Dowdy (to be published in 1982).
(b) Argonne National Laboratory 1981 (Draft).

In addition to the private development just discussed, DOE is involved in DISC research with FY80 funding of about $600-700,000 (Sandia National Laboratories 1980). The following are efforts and labs included in the program:

- fuel injection experiments and combustion computer models - Princeton
- measurement techniques for velocity, temperature, and species concentration - Sandia
- computer models - Lawrence Livermore and Los Alamos
- DISC engine test data - General Motors (nonfunded partner).

The significant barriers to DISC technology are technical. One nontechnical barrier (that is actually technical, in a sense) is future legislated emission standards. The DISC engine will require conventional emission controls to meet stringent standards, including injection timing retard, inlet air throttling, cooled exhaust gas recirculation, and catalytic converters.[a] Additionally, particulate emissions are on par with diesel engines and therefore may raise significant health concerns.

Two other nontechnical issues, cost and fuel availability, will not be barriers if the DISC engine can be developed successfully. Costs should be very much in line with conventional Otto-Cycle engines. DISC engines of the TCCS type will be able to burn almost any type of fuel. Wide boiling range fuels, which are unsuitable for Otto and diesel engines, can be produced about 5% more efficiently than gasoline, further increasing the conservation potential of the DISC.[b]

Current research programs address the significant technical questions related to DISC development. An enhanced effort might prove beneficial in the area of basic combustion research. This area offers long-term and high-risk, but potentially significant rewards that might not ordinarily be pursued by the private sector.

4.4.2 Improved Diesels

The diesel is a highly developed and conventional internal combustion engine. In many ways it resembles the Otto-Cycle engine; the major difference is the

(a) Dowdy 1982.
(b) Argonne National Laboratory 1981 (Draft).

diesel's reliance on compression ignition rather than a spark plug to ignite the air/fuel mixture. Diesel engines have been used widely in trucks for many years. Automobile use has been more limited, primarily because of the diesel's poor low-speed power characteristics. As fuel economy has surpassed performance in importance to American motorists, the diesel has received increased attention as an automobile power plant.

The diesel's fuel economy advantage is due to higher compression ratios and absence of throttling losses. The advantage is significant. Current automobile diesels provide 30 to 70% improvement over gasoline engines in similar automobiles over the EPA driving cycle (The Aerospace Corporation 1980). This figure should be examined carefully, however. Part of the advantage is due to lower power-to-weight ratios (poorer performance) found in diesel automobiles. For equivalent performance one source predicts the diesel advantage in fuel economy at 26 to 36% (Gorman, Heitner and Mority 1979). A second factor should be considered. Diesel fuel contains about 11% more energy on a volume basis than gasoline. For equivalent performance and an equal energy content comparison, then, the real fuel economy advantage of the diesel is 15 to 25%.

Diesel engines also have disadvantages, most notably, lower acceleration, gradability, and top speed capability compared to spark ignition engines. Cold starting also can be a problem, although diesels generally have compression ratios higher than optimal to help alleviate this problem. Increasing concern is being focused on diesel emissions. The diesel's hydrocarbon emissions are roughly the same as spark ignition engines. Because of lean combustion, CO emissions are decreased, whereas NO_x emissions are increased compared to the Otto engine. Currently, unregulated emissions such as particulates and odor-causing organics may pose the most serious threat to the diesel's future. Particulates have been shown to be mutagenic and studies of carcinogenesis are being conducted. Sources from several manufacturers, Daimler-Benz, Ford, General Motors, and Peugeot, state that no technology currently exists to meet the proposed 1.0 g/mi NO_x standard and 0.6 g/mi particulate standard proposed for 1982 (The Aerospace Corporation 1980). Some believe that without emission, the diesel may be legislated out of existence.

Several technological innovations are currently being researched for diesel applications. The most significant is the direct injection (DI) diesel for automobiles. Large truck diesels use DI in which the fuel is injected directly into the cylinder. All automobile diesels use a different concept called indirect injection (IDI), in which the fuel is injected into a prechamber where it ignites and then expands into the main cylinder. IDI diesels are used in automobiles for several reasons. They are quieter, and have lower emissions of HC and NO_x and greater high-speed capability. Their one drawback is reduced efficiency, caused by pressure loss across the prechamber throat, heat loss to prechamber walls, poor flushing of exhaust components from the prechamber, and richer combustion (leading to lower temperatures). Use of the DI diesel in automobiles could mean significant fuel economy increases.

Other improvements in diesel engines are also possible. Combined water injection and exhaust gas recirculation have been shown to significantly reduce NO_x (from 1.5 to 0.3 g/mi), slightly reduce HC and CO, and improve fuel economy. Long-term advances may include variable compression ratios to improve startability and part-load performance, spark plugs for positive ignition timing, throttling to reduce smoke, valve selectors to close off cylinders when full power is not needed, and air bearings to reduce friction. In addition to these engine modifications new engine configurations are possible, such as adiabatic turbocompound engines and organic Rankine bottoming cycles. The former is addressed in the following section of this study.

The DI diesel presents the greatest conservation potential of diesel improvements. Because the DI engine is already used in trucks, this technology applies only to automobiles. Therefore, the energy use addressed is the 10 quads per year currently used by automobiles (see Table 4.1). In Section 4.1, scenarios that project automobile energy use to be between 5 and 14.3 quads per year were presented for the year 2010. As previously mentioned, IDI diesel engines offer a real conservation potential of 15 to 25% over gasoline engines. Estimates of the additional improvement from the DI diesel are quite consistent: Oldsmobile - 10%, JPL - 10%, Ricardo - 15%, Volkswagen - 10% to 15% (Gormon, Heitner and Mority 1979), and Fiat - 10% (Heywood and Wilkes 1980). In this study the total potential improvement in fuel economy in a change from Otto to DI diesel is assumed to be 30%. Nearly all (97.4%) current automobiles are powered by gasoline engines (Ward's Communications, Inc. 1979a, 1979b, and 1980). Therefore, the ultimate conservation potential of the

DI diesel, assuming full market penetration, is approximately 3 quads per year at current consumption levels and between 1.5 and 4.3 quads per year in 2010 at the CONAES scenarios consumption levels.

Prototypes for automobile DI diesels exist now. With successful development, commercialization could begin by the late 1980s, with full market penetration within 10 to 15 years.

Applied research is required for two types of diesel engines improvements: improved fuel economy and reduced emissions. Indirectly, reduced emissions can lead to energy conservation by making possible the use of more energy-efficient technologies. Research opportunities exist in several areas. The following are some focal points for research on diesel engines:

- reduction of DI diesel emissions
- DI diesel fuel injection systems - This is important for increasing high speed capability.
- health effects of diesel emissions - More information is needed on the effects of diesel emissions, especially particulates. If emissions prove less dangerous than expected, reduced standards could be justified and significant fuel economies could occur. If the opposite findings result, the diesel may have to be abandoned.
- engine component optimization
- emissions controls, such as exhaust gas recirculation, catalytic converters, and particulate traps.

Each of these research activities is critical to the particular area it addresses. However, the diesel's conservation potential possibly can be increased through advances in one area, even though other research activities may not prove successful.

Extensive research is currently being conducted on diesel engines, both by private industry and as part of federal programs. The following summarizes some of the private activities:

- direct injection diesel - BNW, British Leyland, Chrysler, Cummins, Daimler-Benz, Fiat, Peugeot

- engine component modifications, including combustion changer and fuel injection systems - BNW, British Leyland, Chrysler, Cummins, Daimler-Benz, Fiat, Ford, General Motors, Isuzu, Nissan, Peugeot, Toy Kogyo, Toyota, Volkswagen
- electronic fuel injection - Chrysler
- emission controls, including exhaust gas recirculation, catalytic converter, water injection and emulsions, particulate traps and trap oxidizers, fuels and lubricants, and noise emission and control - Bosch, BNW, British Leyland, Chrysler, Cummins, Daimler-Benz, Fiat, Ford, General Motors, Isuzu, Nissan, Peugeot, Toy Kogyo, Toyota, Volkswagen
- emissions and measurement technology - BNW, British Leyland, Chrysler, Daimler-Benz, Fiat, Ford, General Motors, Peugeot, Volkswagen
- health effects - BNW, CCMC, Chrysler, Daimler-Benz, General Motors, Peugeot, Volkswagen, Volvo.

The following summarizes some of the government research activities:

- low compression diesel - Cummins
- component optimization, including combustion chambers and injection systems - Chrysler, Fiat, Ricardo, Physics International
- emission controls, including exhaust gas recirculation, catalytic converter, particulate traps and scrubbers, fuel composition, and noise control - Chrysler, Fiat, Ricardo, SWRI, Engelhard, Cummins, Purdue
- emissions and measurement technology - SWRI, Chrysler, Fiat, Ricardo, Michigan T.U., A.D. Little, Inc.
- health effects - Battelle-Columbus, LITRI, MIT, Oak Ridge
- manifold analysis - Science Systems and Software
- Raman spectroscopy - General Electric
- Swirl Stabilized Combustion - Cornell

The conservation potential of diesel technology is constrained by one overwhelming nontechnical barrier - emissions. In one respect emissions can be considered a technical problem because more stringent emissions standards will require technical solutions. However, the perceived health effect of emissions and the degree to which they are regulated will be based mostly on nontechnical concerns.

Other nontechnical barriers are also in question. Drivability aspects of diesels are inferior to spark ignition engines. Acceptance of the reduced performance will most likely occur with the public's realization of the diesel's improved fuel economy. Odor and smoke also pose questions of public acceptance.

More R&D is required to realize the full conservation potential of the DI automobile diesel (25 to 40% improvement in fuel economy). Even without this research the IDI diesel offers a conservation potential of 15 to 25% over conventional engines. However, some research will also be required in emissions control to maintain this advantage as emission standards become more stringent. From this brief survey, existing research programs appear to be addressing the bulk of the research opportunities pertaining to IDI and DI diesels.

4.4.3 Adiabatic Diesels

Most of the energy contained in the fuel burned in an internal combustion engine is rejected as waste heat. Over the EPA driving cycle a typical automobile rejects 29% of the fuel's energy to the cooling system and 33% to the exhaust (see Figure 4.1). Recovery of even a portion of this energy could present an enormous energy conservation potential.

The adiabatic diesel engine is designed to exploit this potential. In this concept the cooling system is entirely eliminated and the engine is allowed to run very hot. Peak cylinder and piston temperatures are 1700 to 2000^{o}F compared to 500 to 600^{o}F in a conventional diesel (DOE 1979; OTA 1979). In this engine ceramic and ceramic-metal composite parts must be used to withstand the extreme temperatures. Low-friction nonlubricated surfaces must also be developed. The extra energy not rejected in the cooling system is passed to the exhaust stream. To recover this energy a turbine is added to the engine, resulting in a configuration known as turbocompounding. The turbine is connected to the engine drive shaft with a fluid coupling. Plans call for adiabatic diesels to also use turbocharging. In this scheme the air charge passes through the turbocharger compressor, into the cylinders, through the turbocharger turbine, through the power turbine, and then is exhausted. One other modification is also being considered. The power turbine could be replaced with an organic Rankine cycle or the Rankine cycle could be added after the turbine. In the latter alternative the result is a turbocompound, combined-cycle engine that includes a diesel engine, turbocharger, power turbine, heat exchanger (evaporator), and organic Rankine cycle - a considerable amount of hardware.

The adiabatic diesel (which will be considered to be turbocompounded for the remainder of this report) has two advantages, power and efficiency. Emissions will probably be a problem, however. Current research is concentrated on military applications for which emissions are not considered (aside from smoke). A second drawback results from the complexity of the concept, which may not be suited to automobile applications. The major current U.S. study is looking only at engines over 500 hp. One source cautions that the engine may not be suitable for engines under 100 hp (DOE 1979). Others think the minimum practical size is even higher. At least one source recommends the concept not be pursued for automobile applications (Kerrebrock and Kolb 1979).

To calculate its energy conservation potential, the adiabatic diesel is conservatively assumed to have a potential only in truck applications. From Table 4.1, the yearly energy use in trucks is about 5 quads. If the CONAES scenarios for automobiles discussed in Section 4.1 are extended to trucks, consumption in 2010 for trucks could range from 2.5 to 6.9 quads per year. The adiabatic diesel engine is estimated to be about 25% more efficient than a turbocharged diesel. Assuming maximum market penetration, the ultimate conservation potential is approximately 1.25 quads per year at current consumption levels and between 0.63 and 1.73 quads per year in 2010 at consumption corresponding to the CONAES scenarios.

Full development of the adiabatic diesel is probably several years off, although Kyoto Ceramic of Japan plans to have an all ceramic diesel prototype on the road by 1984. Initial production can probably not be expected until at least 1990, with full market penetration following in 10 to 15 years.

Research is required to increase the efficiency and durability of adiabatic diesel engines. The following include specific research activities that are necessary if the adiabatic diesel engine is to achieve its full conservation potential activities:

- ceramic components - Practical ceramic components with acceptable durability and cost must be developed.
- friction - High temperatures in the adiabatic diesel make the use of conventional lubricants impossible. Methods to reduce mechanical friction between solid bearing surfaces must be developed.
- emissions - Emissions from adiabatic diesels must be characterized. If emissions are found to be unacceptable, practical control methods must be developed.

Cummins is the only U.S. manufacturer working on adiabatic diesel development. Specific research activities include endurance demonstrations; development of ceramic piston caps and ceramic components for the piston, cylinder liner, cylinder head, and valve head; and development of a low-friction, turbocharged engine using no lubrication. The Cummins program is funded by the U.S. Army.

Emissions and cost are two significant nontechnical barriers affecting the conservation potential of the adiabatic diesel engine. Satisfactory emissions will have to be demonstrated for the engine to reach its full potential. Cost will always be a concern. Early engines are projected to cost several times more than standard diesels, and even with ultimate technology and production rates, costs are expected to be no less than double (OTA 1979).

No practical adiabatic engine currently exists that could demonstrate improved efficiency over a conventional diesel. The conservation potential of the adiabatic diesel is entirely dependent on further R&D.

4.4.4 Stirling Engines

The Stirling engine was invented in 1816 by a Scottish clergyman and later developed by the Dutch for use with portable generators during World War II.

The Stirling cycle has the highest theoretical efficiency of any heat engine cycle and therefore has received considerable attention in recent years as an alternative automotive power plant. The Stirling engine is an external combustion, generally closed-cycle machine in which a working fluid is alternately heated and cooled in an enclosed working space. Although any gaseous working fluid is possible, automotive Stirling engines will use hydrogen to achieve the highest possible efficiencies.

The Stirling engine has many potential advantages over conventional Otto-Cycle engines. The continuous, external combustion process has the potential for reduced emissions and quiet, vibration-free operation and lends itself easily to combustion of alternative, low-quality fuels. Because the engine has better low-speed torque characteristics than Otto engines, similar performance can be achieved with lower horsepower. Finally, the Stirling engine has excellent part-load performance and actually has higher efficiency at low loads. This quality makes the engine especially suited for an automobile, in which the engine very seldom operates at full power.

The Stirling engine also possesses several inherent disadvantages. Closed-cycle operation makes power control more complicated and requires the cooling system to reject twice as much heat as is required in internal combustion engines. Furthermore, the closed cycle requires heat addition through a complex and costly heat exchanger (called the heater head). The Stirling engine is heavier than the Otto engine and has a large mass of hot parts that must be warmed up when starting. Also, the Sterling's auxiliary loads are higher than conventional engines. One of the most significant difficulties in Stirling engineering is maintaining the high-pressure hydrogen in the working space. Finally, permeation through the heater head and leakage around the piston rod seals present problems.

Table 4.1 shows that highway vehicles currently consume about 15 quads of gasoline and diesel fuel each year. Of this total roughly 10 quads are for automobiles and 5 quads are for trucks. The CONAES scenarios project energy consumption of 5.0 to 14.3 quads per year in automobiles and 2.4 to 6.9 quads in trucks in 2010. The DOE Stirling engine program intends to produce an engine that is 30% more efficient than a conventional automobile engine over the EPA driving cycle. Stirling engines could also be used in trucks, although the fuel savings in a truck would be somewhat less. First, trucks already use diesel engines that are more efficient than automobile Otto engines, and secondly, trucks can be expected to experience more highway mileage, where the efficiency advantage of the Stirling is reduced. Assuming a 30% improvement for automobiles, a 15% improvement for trucks, and total penetration in both markets, the Stirlng engine has an ultimate conservation potential of almost 4 quads per year at current levels of consumption and 2.7 to 7.7 quads per year at consumption levels corresponding to the range of CONAES scenarios.

The DOE program's goal is a prototype advanced Stirling engine by 1984. Even with a successful demonstration, the engine most likely will not be mass produced before 1990, and one source indicates commercialization may not occur until 2000 (OTA 1979). After initial commercial introduction the Stirling engine could achieve full market penetration within about ten years.

Several sources have identified research and development opportunities for Stirling engines, including automobile manufacturers, (Kitzner 1980), DOE (1979), government laboratories (Jet Propulsion Laboratory 1975; DOE 1979), and engine manufacturers (DOE 1979). Surprisingly, these sources generally all focus on four areas, listed below roughly in their order of importance.

1. Heater head - Several problems must be solved with the heater head. Because of high temperatures (700-800^{o}C), current designs employ expensive superalloys in the heater head. Lower cost materials are needed. The heater heads are configured in complex geometries using involute tubes. Either fabrication costs must be reduced for these complicated shapes or simpler designs must be developed. Finally, the hydrogen permeation through the heater head must be reduced to minimize the need for hydrogen recharging. Ultimately, ceramic heater heads that will solve these problems may be developed, although they are not the focus of current research.

2. Piston rod seals - Much controversy surrounds this point, with some claiming the problem is solved and others claiming it will never be solved. A system needs to be developed that will adequately seal the working space (oil in the working fluid ruins efficiency), have low friction (to improve fuel economy), and be reliable and durable (to eliminate costly repairs).

3. Control system - Regulating power in a closed-cycle engine is not a simple task. A method that will provide control over a wide range of power levels, provide quick response, and not be too bulky or costly must be developed.

4. Fuel economy - The Stirling engine is predicted to have excellent fuel economy, yet further refinements are needed if it is to achieve its full potential. Possible research activities include developing more efficient combustors, developing better combustion control, optimizing the engine/power train combination, reducing conduction losses in the engine, minimizing auxiliary loads, improving the regenerator, and increasing heater head temperature. Studies at United Stirling of Sweden indicate that raising the heater head temperature from 720 to 820^{o}C will have a minimal effect on fuel economy, an improvement of about one mile per gallon. This minimal improvement will occur because automotive Stirling engines will be most heavily used at the low end of the load map, where efficiency gains from higher temperatures are negated by increased conduction losses.

Each of these four research areas is important to Stirling engine development. The first two should be considered critical, while the last two will be necessary for the engine to reach its full potential. These research requirements are largely the same problems that have been identified since the early years of modern Stirling engine development.

General Motors and Ford both spent private money to develop the Stirling engine during the early 1970s. One source estimates the level of their effort at about $6 million per year by each company (Jet Propulsion Laboratory 1975). Currently, a large amount of Stirling research is being funded as part of the DOE Stirling engine program. Approximately $21 million was spent in FY80 with over $120 million expected to be spent between 1975 and 1984. The following summarize specific research activities in the DOE program and the companies making the effort:

- advanced Stirling engine by 1984 with 30% better fuel economy than a comparable Otto engine - Mechanical Technology, Inc., United Stirling of Sweden (USS), and American Motors General. This is the major thrust of the DOE program with anticipated funding from 1978 to 1984 of $90 million.

- elevated heater head temperature - USS
- improved piston rod seal - USS
- new heater head design - USS
- quieter drive mechanism - Ricardo
- hydrogen permeability in various heater head materials - NASA-Lewis
- heater head tube coatings to reduce hydrogen permeation - ITT Research Institute
- piston rod seal lubrication tests - Shaker Research Corporation.

The Future of the DOE Stirling engine program is uncertain at this time due to changed policy considerations of the new administration. The program has been recently restructured to emphasize component research rather than vehicle demonstration (DOE 1979).

The major nontechnical barrier affecting the Stirling engine is cost. Current designs would be quite expensive in mass production for three reasons: complexity, expensive stainless steel and suuperalloy materials, and expensive equipment required to fabricate and machine the materials. One source estimates that the Stirling engine will cost 55% more in mass productin than an Otto engine of equivalent horsepower.[a] Because of better low-speed torque characteristics, a Stirling engine equivalent in size to an Otto engine will not be required for equivalent performance. An early Jet Propulsion Laboratory (JPL) study, which assumed reductions in material costs, estimated that a Stirling engine with equivalent performance will cost about 25% more, or about $600 per engine in 1981 dollars, than an Otto engine.[a] However, consumers are currently paying a premium of this much or more for fuel-efficient diesel engines. Therefore, if expected material cost reductions can be achieved, cost should not be a hindrance to market penetration. Current material cost estimates are, however, several times the value assumed in the JPL study.

A second, related nontechnical barrier concerns material availability. Present heater head materials, in addition to being very expensive, may not be available in the quantities necessary for substantial market penetration.

(a) Dowdy 1982.

Therefore, the real solution to the materials questions seems to be identification or development of less expensive, more common materials for engine components rather than reduction of fabrication and manufacturing costs using present materials.

The conservation potential of the Stirling engine is entirely dependent on R&D technological improvements. Current Stirling engines have no conservation potential and are, in fact, less efficient than conventional internal combustion engines.

The existing DOE Stirling engine program is already addressing the significant technological problems for Stirling engine development. The funding level is within the range proposed by JPL for effective technology development ($16-$28 million/year in 1981 dollars).[a] Without the DOE program little or no Stirling research can assumed to be conducted in the United States. The major automobile manufacturers have shown no inclination to pursue the Stirling engine, even with federal support.

4.4.5 Brayton Engines

The Brayton engine is a relative newcomer to the heat engine field. Practical Brayton engines were not demonstrated until the 1940s, although since then, they have been highly developed for aircraft applications. A Brayton cycle can be implemented in a reciprocating machine, although the more typical application uses rotating components and is commonly referred to as a gas turbine. The gas turbine is somewhat unique among heat engines in that the working passes through separate, identifiable components where it is compressed, heated, and expanded. Normally a regenerator is added to the cycle to recover some of the high-temperature energy that is exhausted by the turbine. Brayton engines can be closed-cycle, in which any gaseous working fluid may be used, or open-cycle, where air is the working fluid. Current automotive development efforts concentrate solely on the open-cycle variety; therefore, the Brayton engines considered in this study will be open-cycle gas turbine engines. Two engine configurations are currently under study. The single-shaft engine (SS) employs a compressor and a turbine mounted on the same rotating shaft. A second type, known as the free-turbine Brayton engine (FT), uses two shafts,

(a) Dowdy 1982.

with the compressor and a turbine to drive the compressor (gasifier turbine) on one shaft and a second turbine to supply output power (power turbine) mounted on a second, independent shaft.

Noteworthy differences do exist between the SS and FT designs. In the FT configuration the two shafts are free to rotate at different speeds. Therefore, the compressor and gasifier turbine can spin at a constant, optimal speed while the speed of the power turbine varies to adjust to changing loads. This capability makes use of conventional automotive transmissions with an FT engine. In the SS design the power turbine is constrained to rotate at the same speed as the compressor, which must rotate at a relatively constant speed to maximize efficiency. In this type of gas turbine a continuously variable transmission is normally required to attain acceptable torque-speed characteristics. The SS design does have the advantages of a simpler design, fewer moving parts, and fewer bearings and seals.

Gas turbine engines of either type have several advantages over conventional internal combustion engines. They have few moving parts, low vibration, and the potential for long life with low maintenance requirements. Gas turbines have higher power-to-weight ratios than Otto engines and much higher power-to-weight ratios than Diesel or Stirling engines.[a] Excellent low-speed torque characteristics mean that smaller engine sizes can be used to achieve equivalent performance. The continuous combustion process in the Brayton cycle carries the potential for reduced emissions and use of alternative, low-quality fuels.

Gas turbine engines of either type also have disadvantages compared to the conventional Otto engine. The gas turbine operates best at a relatively constant, very high speed, so fuel consumption is high even at idle or light loads. A second disadvantage is the expensive materials and manufacturing requirements for current designs. Also, the engine does not provide much engine braking when fuel is cut off. Finally, the turbines do not scale down in size well; as sizes become smaller, rotor trip clearances and channel pressure drops become relatively more significant.

(a) Dowdy 1982.

As Table 4.1 indicates, current energy use by highway vehicles is approximately 15 quads per year, roughly split between 10 quads for automobiles and 5 quads for trucks. The CONAES scenarios discussed in Section 4.1 project energy use in highway vehicles from 7.4 to 21.2 quads per year in 2010. The Brayton engine could potentially displace all conventional automotive power plants, although its efficiency benefit at the smaller engine sizes predicted for future cars (approximately 50 hp) has been questioned. The goal of the gas turbine program is a 30% improvement in fuel economy over the EPA driving cycle. The present analysis assumes that this value can be attained for all automobiles. The Brayton engine has an even greater potential in truck applications. Brayton engines are more efficient in the larger sizes and at the steady speeds often used by trucks. Because they would displace a relatively efficient diesel engine, however, the efficiency improvement potential in trucks is still assumed to be 30%. Assuming a 30% improvement in automobile and truck fuel consumption and full market penetration, the maximum energy conservation potential of the Brayton engine is almost five quads per year at current consumption levels and from 2.2 to 6.4 quads per year under the CONAES scenarios for 2010. Efficient Brayton power plants could not likely be mass produced before 1990. After that it would take approximately ten years to saturate the market.

Several technical barriers stand in the way of successful implementation of the Brayton engine as an automotive power plant. The following summarize major barriers:

1. ceramic components - This is the single most critical issue facing Brayton engine development. Most sources agree that the gas turbine will not demonstrate significant fuel economy benefits over conventional internal combustion engines without extended operating temperatures, which will require high-temperature ceramics. Ceramic components also carry the potential for reduced cost and elimination of a dependence on scarce, superalloy materials. Research activities should be aimed at developing both materials suitable for Brayton operating conditions and mass production techniques that will allow cost-effective component fabrication. The ultimate goal in ceramic technology would be an inexpensive, durable turbine rotor that could

be cast as a single piece. Ceramics will also be necessary in combustors, stators, diffusers, and scrolls. A related area of research need is improved bonding and joining techniques using ceramics.

2. combustor - The continuous combustion process in the Brayton cycle provides a potential for low emissions, but further technological advances will be required to meet future, more stringent emission standards. Premixed, prevaporized combustors must be developed to replace conventional diffusion-flame types. Variable geometry combustors will be required to maintain acceptable efficiency under part-load conditions, which are so important for automobile performance. In the longer term catalytic combustors may prove to be important in Brayton engineering. This technology promises ultra-lean combustion, low emissions, high efficiency, stable combustion, low-pressure drop, and multifuel capability. Research also is required on catalytic materials and high-temperature substrates.

3. aerodynamics - Further work is needed to optimize the aerodynamic performance of Brayton engine rotating components. To date automotive Brayton technology has relied heavily on aviation Brayton engineering in which components are designed for much different operating conditions. Compressors and turbines that have acceptable performance over a range of load and speed conditions must be developed. Variable inlet guide vanes and diffusers will be necessary to improve part-load characteristics and engine braking capabilities.

Several technological research needs exist in the Brayton program. However, one area, ceramics, is generally considered the most crucial and by many, the most questionable. Without developments in ceramics the Brayton engine will probably not have a future as an automotive power plant.

All three of the major U.S. automobile manufacturers have dedicated private funds to Brayton engine research, with a substantial effort occurring during the 1960s and early 70s. One source estimates their funding commitment during this period was approximately $6 million per year for each manufacturer (Jet Propulsion Laboratory 1975). Private research is still continuing at several manufacturers. Emphasis is being placed on truck applications by several companies, including General Motors, Volvo, Volkswagon, Nissan, and Toyota. A consortium of Garrett/Mack/KHD is working on a large truck turbine that may prove to be the first commercial application in a highway vehicle.

Currently, a large amount of automotive Brayton research is being conducted within the DOE gas turbine program. The focus of this activity is development of an advanced Brayton engine with 30% better fuel economy than a conventional Otto-cycle engine over the EPA driving cycle. Federal funding in FY80 was about 30-$40 million. Three teams are competing in the effort. A summary of the work of the three major contracts plus some related projects is given below:

- free-turbine regenerative gas turbine with 4-speed automatic transmission - Detroit Diesel Allison/Pontiac
- single-shaft regenerative gas turbine with variable stator torque convertor and automatic overdrive transmission - Garrett/Ford
- single-shaft regenerative gas turbine with continuously ariable transmission and response assist flywheel - Chrysler/Williams
- demonstration of gas turbines in intercity buses - Greyhound
- demonstration of gas turbines in intracity buses - administered by Booz, Allen, and Hamilton
- ceramics research - Corning, Carborundum, Ford, AiResearch Casting Company, NGK of Japan, and Pure Carbon Company.

No nontechnical barriers exist that are significant enough to limit the Brayton engine's potential, assuming the technical problems can be solved. Initial demonstration projects indicated that drivers reacted favorably to buses with gas turbine engines. Materials availability will not be a problem if high-temperature components are ceramic. Mass production costs should be roughly in line with costs for advanced Otto engines.

Current Brayton engine prototypes have not demonstrated better fuel economy than conventional internal combustion engines. Any conservation potential the Brayton may offer in the future will be strictly dependent on a successful R&D program.

The major research opportunities relating to the automotive Brayton engine are being addressed in the DOE gas turbine program, although the future of this program may be somewhat uncertain. If the program were curtailed, some research would most likely continue in the private sector. However, the emphasis in most current private research is on the near-term market, which generally means metal engines. Applied research for longer-term needs, most notably development of ceramic engines, could suffer without the DOE program. Significant break-throughs in ceramic technology could alter this position and instill new interest in Detroit in the Brayton engine as an alternative automotive power plant.

4.4.6 Improved Otto-Cycle Engines

Although several alternative automobile engine concepts may hold significant potential for energy conservation, the standard Otto-cycle power plant currently used in automobiles must not be overlooked. Many possible modifications exist that could significantly improve the Otto engines fuel efficiency.

Turbocharging is one possible improvement that is already beginning to be implemented in some production automobiles. A turbocharger uses a small turbine powered by the exhaust gases to compress the incoming air charge. Because more air can be brought into the cylinders, more fuel can be burned and the engine produces more power. If equivalent performance is desired, the size of the engine can be decreased, leading to fuel economies. Turbochargers already have been widely used in diesel engines. Use in gasoline engines also promises improved efficiencies but is a technically more demanding problem. Reliability is more difficult because of the higher temperature of automobile exhaust. The wider-speed range of the gasoline engine causes problems because adequate turbocharging at low engine speeds can lead to over-boost at high speeds. Normally a waste gate, which dumps exhaust at high pressures, must be added to eliminate this problem. Engine knock limits also are a problem. Another problem is turbocharger lag, which is more apparent in gasoline engines because the engine itself is more responsive than a diesel. Finally, turbochargers introduce the disadvantages of lower low-speed torque and higher pressures, temperatures, and engine stress levels.

One variation on turbocharging is supercharging, in which the compressor is driven directly by the engine drive shaft rather than by a turbine. This concept has the advantage of more rapid response. The supercharger also has a potential to have a demand-control system so that the extra power is available only under high-load conditions. Supercharging has a valve selector that also offers fuel economy advantages. This mechanism shuts intake and exhaust valves to certain cylinders, effectively turning off those cylinders during periods of low load. The remaining cylinders can then operate nearer their optimal efficiency points, resulting in an overall more efficient combustion process.

Further efficiency benefits could be gained simply by resizing the Otto-cycle engine's intake and exhaust valves. In current engines, valves are sized for maximum power at wide open throttle and exhaust valves are typically only 70% as large as intake valves. This sizing difference causes the pumping losses over the exhaust valve to be 10 times as large as across the intake valve. Making the exhaust valve as large, or even larger than the intake valve significantly reduces overall pumping losses. A second advantage occurs because the exhaust process is more complete, raising the combustion temperature and efficiency.

Another technology for efficiency improvement is known as the constant speed accessory drive. Every automobile engine has several accessories that are powered by the engine drive shaft, including the fuel pump, water pump, fan, the air conditioning compressor in some cars, and in new cars the air pump. Drive units for these accessories are sized to operate satisfactorily at low engine speeds. As the speed of the engine increases, extra, unneeded power is supplied to the accessories. In the constant speed accessory drive system a variable ratio pulley system is used so that the accessories do not run faster than needed at high speeds. Accessory loads on the engine are therefore reduced and fuel economy is improved.

Finally, several technologies that can be classified together as power train management also have significant conservation potential. These include electronic shift indicators, computer controlled transmissions, and stop-start engines.

As shown in Table 4.1, automobiles, which almost exclusively use Otto engines, consume about 10 quads of energy each year. The CONAES scenarios discussed in Section 4.1 project automobile energy use in the year 2010 to range between 5.0 and 14.3 quads. Each of the Otto improvements just discussed could have some impact on this figure. Turbochargers are projected to improve fuel economy 5 to 15% (Gorman, Heitner and Mority 1979).[a] Assuming a practical value is 10%, the expected ultimate conservation potential would be about one quad per year. Superchargers, especially the demand-control type, may prove somewhat superior, although for a rough approximation their conservation potential can be considered about the same. Valve selectors are expected to reduce fuel consumption approximately 10%, leading to a one quad per year energy savings, assuming full market penetration at current consumption levels or 0.5 to 1.4 quads per year at the consumption levels corresponding to the CONAES 2010 scenarios (OTA 1979). Valve resizing could improve engine efficiency 8% and yield almost one quad per year in energy savings at current consumption levels or 0.4 to 1.1 quads per year under the CONAES 2010 scenarios (Gorman and Heitner 1980). Constant speed accessory drives also represent a conservation potential of almost one quad per year at current consumption levels or 0.25 to 1.43 quads per year in 2010, with fuel economy improvements estimated at 5 to 10% (Gorman, Heitner and Mority 1979; DOE 1979).

TRW, Inc. (1977) estimates that combined improvements to the Otto-Cycle engine could improve efficiency by 25% over current engines. If applied to the entire automotive sector, a 25% improvement would save 2.5 quads per year at current energy use levels and 1.25 to 3.6 quads per year under the CONAES range of energy use levels given for 2010.

All of these technologies represent near-term alternatives. Most could be commercialized in the next couple of years and could reach full market penetration within approximately ten years.

Research and development opportunities exist for each of the technologies for Otto improvement. Several turbocharger research activities are possible. Ceramic turbines would increase durability at high temperatures. Variable geometry for the compressor and turbine would minimize the over-boost problem at high speeds. Smaller intake and exhaust manifolds, lower inertia turbocomponents, and higher turbocharger efficiencies at low-pressure ratios would improve the lag problem. The other technologies require mostly product development and demonstration activities.

(a) Also Dowdy 1982.

Turbochargers are currently the focus of research activity at numerous companies. One source estimates the number of current research programs at 20 world-wide (OTA 1979). The Garrett Corporation is currently researching a constant speed accessory drive system. DOE is supporting a program of basic combustion research, which includes help from the University of California, Massachusetts Institute of Technology, TRW, University of Michigan, SAI, Ford, and Exxon. Specific studies include analysis of flammability limits, fluid motion, turbulence levels, heat transfer, and ignition processes; measurement of emissions; and development of combustion computer models. Funding for the DOE program was approximately $700,000 in FY80.

Nontechnical barriers face a couple of the conservation technologies discussed. Repair, maintenance and cost questions surround turbocharger development activities. For example, the addition of a turbocharger in a 1978 Buick cost $550 (OTA 1979; Gorman and Heitner 1980). Cost estimates for mass production vary from $25 to $125 (Gorman, Heitner and Mority 1979). Cost considerations will probably not be too significant for constant-speed accessory drives as cost estimates are about $20 per unit (Gorman, Heitner and Mority 1979). This technology faces another nontechnical barrier, however. Because of idiosyncrasies in the EPA mileage test, the benefits of a constant-speed accessory drive may not show up. Therefore, the public's perception of this concept's conservation potential may be in doubt.

Much of the turbochargers' conservation potential is already available. More R&D could increase this potential through the development of more advanced units. None of the other technologies are currently commercialized, so some development will be required to exploit their full conservation potential.

4.4.7 Improved Transmissions

Part of the power produced by an automobile engine is dissipated in the drive train before it ever reaches the wheels. Conventional automatic transmissions account for the significant fraction of this loss. A typical automatic transmission has an average efficiency of only 75% (Wolfe 1975) over the EPA driving cycle and accounts for 12% of the energy consumed by the automobile (Jet Propulsion Laboratory 1975). In addition to this direct energy loss a transmission can cause the engine to operate in a nonoptimal regime, further increasing the overall efficiency penalty. Several types of transmissions have been designed, and a few have at one time or another reached commercialization. However, all of the automatic transmissions of today's automobiles are of one basic type and actually consist of two transmission devices, hydrokinetic torque converter combined with a planetary gear set engaged by disc or band clutches. The two- or three-speed gear set provides the major speed reduction with the torque converter supplying extra torque at low speed and smoothing the transition between gear shifts. Control systems can be mechanical, electronic, or hydraulic, with hydraulic the most prominent. Sources of inefficiency in this transmission include torque converter slippage, band and clutch drag, and oil pumping. Further energy penalties result from current design practices that optimize for crisp acceleration rather than efficient operation. Several improvements of alternatives have been proposed for the conventional automatic transmission. They are considered here in four classes.

The first class represents no basic change to the conventional transmission at all. Transmissions could be reoptimized to operate more efficiently and allow more efficient engine operation. The penalty would be reduced acceleration.

A second class of changes includes simple redesign. Tighter tolerance in the torque converter, wider gear ratio, and lower viscosity oil could all improve fuel economy. Tighter tolerance in the torque converter would tend to reduce acceleration and decrease the smoothness of shifting, however.

Carrying the design change one step further leads to a third class of transmission improvements. A wide ratio, four-speed gear set could replace the three-speed set now commonly used. Also, torque converters could be designed with a lock-up feature at high speeds. Finally, variable volume oil pumps would reduce the required oil pumping power.

A more radical change for automobile transmissions would be the use of an entirely new concept, such as the continuously variable transmission (CVT), which is the fourth class of transmission improvements. In this device the gear ratio is infinitely variable, allowing the engine to operate more often at an optimal point on the torque-speed map. For example, at road conditions the fuel consumption is twice as high at the engine speed dictated by conventional transmissions as it would be for the same power at full throttle (where speed would be higher and torque lower). A CVT would push the engine closer to this optimal point. Most CVT designs rely on some sort of belt system with variable ratio pulleys. In addition to the direct advantages, the CVT provides higher power at low speeds, allowing the engine to be smaller for equivalent acceleration. Disadvantages include wear in the pulley-belt system and increased engine wear and emissions due to greater operating times in the low speed/high torque regime.

The technologies discussed in this section all represent improvements to automatic transmissions. Therefore, they are applicable only to automobiles and light trucks with automatic transmissions. Automatic transmissions are used in about 75% of these vehicles (Ward's Communications, Inc. 1979a, 1979b, and 1980), which consume approximately 10 quads of energy per year (see Table 4.1). Under the CONAES scenarios discussed in Section 4.1, automobiles could account for 5.0 to 14.3 quads per year in 2010. Improvements in each of the four transmission classes are considered independently, and full market penetration is assumed to calculate the conservation potential of each one. One source estimates that reoptimization of present transmissions could reduce fuel consumption 10 to 15% (Wolfe 1975). Assuming the 10% value, the conservation potential is approximately 1 quad per year at current energy-use levels and 0.5 to 1.4 quads per year at CONAES 2010 energy-use levels. Design improvements coupled with reoptimization are projected to increase fuel economy 20 to 30% (Wolfe 1975). If a 20% increase is assumed, a savings of 2 quads per year at current energy-use levels could result and 1.0 to 2.9 quads per year at CONAES 2010 energy-use levels.

The literature has several estimates for fuel economy improvement of an advanced, but still conventional transmission with a wide-ratio, four-speed gear set, torque converter lockup, and variable volume oil pump. These estimates include 8% (Jet Propulsion Laboratory 1975), 8 to 18% (OTA 1979), 15% (Gorman and Heitner 1980) amd 15 to 20% (Gorman, Heitner and Mority 1979). Assuming that 15% is a reasonable value, the conservation potential is about 1.5 quads per year at current energy-use levels and 0.75 to 2.15 quads per year at CONAES 2010 energy-use levels.

A CVT can yield 30% lower fuel consumption at constant speed, less while accelerating (Jet Propulsion Laboratory 1975). Efficiency improvement estimates over a normal driving cycle range from 10% for small cars to 15% for large cars (Jet Propulstion Laboratory 1975). Because automatic transmissions are more prevalent in larger cars, a fleet average value of 15% is assumed, leading to a potential energy savings of 1.5 quads per year at current energy-use levels and 0.75 to 2.15 quads per year at CONAES 2010 energy-use levels.

The first three classes of transmission improvements could all be commercialized by 1985 with full market penetration following in ten years. The CVT has been projected for initial commercialization (10% of market) in 1990 and could reach full penetration within 10 to 15 years (Ward's Communications, Inc. 1981a).

With the exception of the CVT, all of the improvements discussed have received research attention and are near commercialization. Some final development work is required, including integration of the transmission and engine to achieve optimal performance and to minimize emissions.

The status of the CVT is less certain. Development work on specific concepts will be required. Research activities could include development of improved, more wear-resistant bearing surfaces, materials and lubricants for the CVT traction drive, and durability testing of CVT concepts.

Advanced transmission research is being carried out almost entirely by the private sector. Specific programs are almost impossible to identify because publicity is usually withheld until the technology is ready for introduction. One CVT effort is being conducted by Chrysler as part of the DOE gas turbine program.

The various transmission improvements discussed here face various degrees of nontechnical barriers. Reoptimization of present transmissions is a simple and inexpensive alternative, but drivers will have to accept decreased performance. Torque converter modifications, including lock-up features and tighter tolerances, will also lead to poorer acceleration. The CVT will actually allow improved acceleration in addition to the efficiency benefit. However, maintenance requirements for this technology are uncertain.

Design optimizations could be implemented with very little research effort. Thus, if the public accepts reduced performance, a very large portion of the conservation potential of transmission improvements could be realized without much R&D. Redesign activities will require what would more fairly be called development, rather than research. Realization of the CVT's conservation potential still requires significant R&D activity. Some sources doubt that this potential will ever be achieved. A University of Michigan survey of personnel in the automobile industry revealed such comments as "the CVT is a myth" and "no improvements in a potentially practical engine have been demonstrated" (Ward's Communications, Inc. 1980).

4.4.8 Friction Reduction (Tribology)

Figure 4.1 shows that engine friction accounts for 7% of total energy use in an automobile or approximately 18% of indicated horsepower. Other friction losses occur in the transmission, axle, and wheel bearings. Reduction of these losses to friction would result in improved vehicle fuel economy.

The engineering field that addresses friction is known as tribology. "Tribology" is derived from the Greek word "tribein," meaning "to rub," and is defined as the multidisciplinary science dealing with the physical, mechanical, metallurgical, and chemical phenomena of interacting surfaces in relative motion. As such, tribology encompasses the engineering areas of friction, wear, lubrication, solid and fluid mechanics, lubricant and bearing material properties, and surface metrology.

Energy savings from friction reduction are possible. About one third of all energy generated has been estimated to be consumed by friction (Johnson 1977). Approximately one third of this wasted energy could be recovered by proper design to minimize friction and wear (Engineering Times 1980). In addition, reduced friction would result in decreased wear, thus requiring fewer replacement parts and thereby conserving materials as well as energy. The United Kingdom recognized the importance of tribology about a decade ago and established the National Center of Tribology at Risley, England, to provide a focal point for tribological research.

As shown in Figure 4.1, of the total energy use in an automobile, piston rings and other engine friction accounts for 7%, which represents about 20% of the engine's total useful energy output. Thus, a 25% reduction in these losses would result in a 5% reduction in total automobile energy use, assuming that exhaust and cylinder cooling losses continue to account for a constant percentage of energy use. If such an improvement were made in all the automobiles in the U.S., an energy savings of about 0.5 quads would result under current consumption patterns or 0.25 to 0.72 quads at CONAES 2010 energy-use levels.

Transmission and axle friction account for 3% of total energy use, or 12% brake horsepower. A 25% reduction in these energy losses translates into a 3% reduction in automobile energy, or about 0.3 quads per year at current consumption levels and 0.15 to 0.43 quads under the CONAES scenarios.

A key research opportunity to reduced engine friction is an improved understanding of the fundamental mechanisms of wear particle generation and material wastage in sliding and abrasive wear situations. Abrasive wear occurs at the piston ring-cylinder wall interface. Frictional losses and blow-by losses increase as the materials wear. Research would point the way to developing improved materials and lubrication concepts.

The following are specific recommended research projects relating to the tribology of piston rings (Pinkus and Wilcock 1977):

- development of an analytical model of ring lubrication
- piston ring optimization studies
- measurement of piston ring losses
- investigation of piston ring materials and coatings.

Research opportunities also exist in developing improved engine lubricants. Low viscosity lubricants are needed for general use in present and future automobile engines. Fuel additives are needed to improve the boundary lubrication at the piston ring-cylinder wall interface.

Important research opportunities in tribology also exist in support of the continuously variable transmission and the adiabatic diesel. These opportunities are discussed in the sections dealing with these technologies.

Tribology research, particularly at the more basic levels, is apt to have application to more than one end-use sector. For example, an improved understanding of abrasive wear mechanisms would be useful in designing more efficient automotive and industrial machinery. Thus, many of the existing research programs and research areas that are listed in reference to industry in Section 5.4.13 are applicable to automotive tribology research as well. They are therefore not listed here.

Because tribology research has multisector applicability, this important research area needs to be considered from a generic research perspective. The end-use perspective of this study clearly identifies the usefulness of tribology to energy conservation in specific technologies in specific end-use sectors. It does not, however, rigorously evaluate the potential energy savings across all end-use sectors of each individual piece of research. Such systematic study would be highly useful in generating a cost-effective research agenda in tribology.

4.4.9 Reduced Rolling Resistance

As shown in Figure 4.1, tire rolling losses account for 6% of total automotive energy use, or approximately 24% of brake horsepower. For a typical heavy truck, tire rolling losses can be twice this high (Schuring 1980). However, since the 1973 oil embargo, tire rolling losses have improved by more than 25% (Schuring 1980). This reduction is due to the rapidly increasing use of radial tires, lower loads, higher inflation pressures, and tire materials having lower hysteresis (deformation) losses.

The progress to date in tire rolling loss reduction is indicated by the substantial shift to radial tires in both automobiles and heavy trucks. Some 80 to 90% of the tires now appearing on new cars are radials. Since 1975, inflation pressures have gone up an average of 1.5 psi each year and tire inflation pressures of 40 psi are projected for 1985. Automotive suspension designs are shifting slowly to accommodate these new tire characteristics.

The rolling resistance of an individual tire is a strong function of load, temperature (determined by length of travel) and speed. Currently, the "average" rolling resistance of automotive tires is about 6.5 to 8 lb per 1000 lbs of load on the tire. The fleet average is roughly 8 lb and 6.5 lb is about the state-of-the-art. The best possible rolling resistance has been stated to be in the 4 to 5 lb range, but that resistance could be attained only by sacrificing other necessary tire characteristics such as handling, braking and durability (Hill and Moore 1978). An estimated additional 5% reduction in rolling resistance can be made relative to the current state-of-the-art. This translates to a fuel reduction of about 1.2%.

Table 4.1 shows that autos and trucks use about 15 quads of energy, 97% of which is petroleum based. The range of CONAES scenarios projects automotive energy consumption to be from 5.0 to 14.3 quads in 2010. If truck energy consumption follows automotive energy use, total highway vehicle use in 2010 would be between 7.4 and 21.2 quads. A 1.2% fuel use reduction in highway vehicles represents 0.18 quads at present consumption levels, or 0.09 to 0.25 quads at CONAES energy-use levels.

Because tire technology is complex, developments are largely made on an empirical basis. However, the tire companies have been successful in achieving significant reductions in rolling resistance using this empirical approach. To better understand the complex interactions of the tire components and their effect on fuel economy, accurate models (algorithms) need to be developed. The recent review by Schuring (1980) indicates that the state-of-the-art tire models give sharply divergent predictions. These variations are the result of model inadequacies that must be resolved before accurate predictions can be made. Improved models could be used to more accurately assess the effects of different tire materials, cord and belt geometries, tire geometries, tread pattern and depths, etc., on rolling resistance and other performance characteristics. The models would speed tire research, indicate new directions to take, and facilitate optimization of tire characteristics.

As tire inflation pressures rise, maintaining tire pressures in the field becomes more and more important to achieve the fuel economy gains promised by the high inflation pressures. The average automobile operator has not maintained pressures well in the past. Poor maintenance is compounded by the fact that high-pressure tires will leak down faster. Past attempts by the U.S. Department of Transportation (DOT) to educate motorists about tire maintenance have not been effective. Some sort of warning devices may be effective in reminding the motorist. A study of consumer attitudes could be useful in understanding how to bring about a public awareness of tire pressure maintenance. Mechanism studies of tire air loss could be very useful in indicating methods for slowing air pressure loss.

Changes in tire rubber compounds could have a measurable effect on rolling resistance, but the tread compound must be designed for other important requirements such as wear, traction, and crack resistance. According to conventional wisdom, only 15 to 20% of rolling resistance improvements will come from the compound; the rest will come from developments in tire, geometry, construction, etc. The hysteresis loss characteristics of available rubbers are well known. The compounds are formulated to get a favorable balance of all properties. Development of the models previously mentioned would definitely aid compound selection and development. Given the ability to specify desirable new compound characteristics, applied research on rubber compounds could possibly effect additional rolling resistance reductions.

Additional energy savings beyond those possible with conventional tires may be possible through use of radical tire and suspension designs. Such designs might use very hard tires combined with new types of suspension to reduce rolling resistance, while still providing adequate cushioning and performance.

Currently, DOT is spending about $10,000 per year on tire rolling resistance. Private tire companies are also involved in tire research, but, as mentioned previously, much of the private R&D is empirically based. Although development of specific products is best left to private manufacturers, government support of modeling and data collection might be an appropriate way to foster development of techniques for reducing rolling resistance in highway vehicles.

4.4.10 Vehicle Weight Reduction

Energy-use reductions in highway vehicles (autos, trucks, and recreational vehicles, buses, motorcycles) can be brought about by a combination of two general strategies: improved mechanical efficiency (engine, drive train, tire, aerodynamics) and reduced weight. At constant mechanical efficiency, a vehicle's energy use is proportional to its weight (i.e., halving weight halves fuel use) and weight reduction has a powerful effect on fuel economy.

General strategies for weight reduction are downsizing (making vehicles smaller), more efficient use of materials (thinner gauge sheetmetal, mechanical design optimization, combination of functions, etc.) and the use of lightweight materials such as plastics, aluminum, magnesium, and composites. Downsizing mechanical design optimization and efficient use of materials are engineering functions carried out as part of the overall vehicle design process. As such, they are the responsibilities of private manufacturers. On the other hand, lightweight materials development is an area that can benefit from applied research and may be generic enough to warrant government attention.

Highway transportation accounts for about 15 quads, 97% of which is petroleum based (see Table 4.1). Autos and light trucks consume 98% of highway energy use. As discussed previously, the CONAES scenarios project a range of energy use for highway vehicles in 2010 from 7.4 to 21.2 quads.

For this analysis the following assumptions are made: 1) any new lightweight material will be incorporated in new vehicles in the year 1985 and after, 2) a 1% reduction in weight will yield a 0.7% reduction in fuel consumption (engine size is replaced and reoptimized for the lighter vehicle) (Gray and Von Hippel 1981; Miller 1975), 3) an X or K car represents the state-of-the-art in vehicle downsizing, efficient material use, and design optimization, and 4) the use of lightweight materials could result in a 400 lb weight drop from a current curb weight of 2300 lb.

The energy conservation potential for highway vehicles is then 1.83 quads at 1978 energy consumption levels or 0.9 to 2.58 quads under consumption levels represented by the CONAES scenarios. Autos and trucks have average lives of 10 and 15 years, respectively. Thus, full replacement would take at least that long. However, high fuel costs would tend to accelerate the scrapping of older, less efficient vehicles.

In general, applied R&D is necessary to better understand and optimize the use of existing lightweight materials, to develop new materials and processes, and to reduce the cost of lightweight materials. Needed research would include studies on forming and fabrication, durability and reliability, and innovative and advanced materials concepts. Specific research opportunities are material dependent. Several broad classes of materials, such as high-strength/low-alloy (HSLA) steels, aluminum alloys, plastics and composites, and magnesium, are receiving widespread attention as lightweight substitutions for existing materials. Some potential research opportunity areas for each of these materials are discussed below.

When strength properties (rather than stiffness) are important, thinner sections of HSLA steels can result in vehicle weight reductions. A large bulk of steel usage is found in stampings and moldings made from sheet material. Research on forming techniques and processing's effects on properties is needed to optimize procedures; the results would be useful in introducing HSLA steels to vehicles. To optimize vehicle reliability, durability, safety, crash worthiness, etc., a firm understanding of fatigue, fracture and corrosion characteristics of HSLA steels is necessary. A better understanding of how microstructure and microchemistry affect materials, properties, and performance is also needed. All of the above research would be highly useful in accelerating the introduction of HSLA steels and would affect the ultimate level of substitution.

Certain forming, joining, casting, and durability characteristics of aluminum specific to automotive applications need additional basic understanding: formability (modeling, characteristics, die design, lubricants), spot welding and adhesive bonding, casting research (modeling, higher strength and ductibility alloys) and structure property relationships. Research in these areas would be useful in expanding aluminum's role.

Plastics play an increasingly important role in the auto industry, not only because of their light weight, but also because new polymers with unusual properties can be synthesized. New polymers with properties tailored for specific auto applications need to be synthesized, and the durability and reliability characteristics need to be improved to increase useful lifetime and reduce the need for repairs and replacement. Research and development of these two types could have a significant effect on total plastic uses.

High performance composites are often expensive and relatively difficult to manufacture in large quantities. Many aspects of processing and behavior of lightweight, lower-cost fiber reinforced polymers need to be better understood. Preparation and fabrication of structure and properties are two general research opportunity areas for both fiber reinforced polymers and metal/polymer laminantes. Applied research is crucial to the development of automotive application of these materials.

Magnesium alloys are very light but they suffer from poor corrosion resistance and generally poorer mechanical properties than steel or aluminum alloys. Fertile areas for research are corrosion prevention, alloy development and casting. Although magnesium has not been cost competitive in the past, applied research might accelerate the transition to magnesium, if the cost picture improves.

Every vehicle manufacturer and material supplier is funding significant efforts in applied research for lightweight materials. Vehicles manufacturers fund research to meet government mandated fuel economy standards and materials suppliers do research to maintain or increase their share of the vehicle mass even as vehicle weights are dropping. Total funding in lightweight materials is probably measured in the hundreds of millions of dollars annually, while the applied research portion of that is in the tens of millions of dollars. This level of research volume probably limits the appropriate government role to very specialized research areas.

Lightweight material innovations must be cost competitive, or offer added advantages such as increased durability, reduced friction, reduced part numbers, or simplified assembly. A principal impediment to new materials is the retooling costs for a material change; often improved older materials require a minimum of investment. Also, the color and texture of a new material must often match those of materials adjacent to them.

Most of the conservation potential of lightweight vehicles is attainable with existing technology combined with engineering. Applied research might be essential for roughly 20% of the conservation potential. The extent of current research is material dependent and needs to be assessed by material. However, such a survey is beyond the scope of this brief overview. Most research applicable to short-term objectives (up to 5 years away) is being done by industry. Research of a more fundamental and long-term nature is probably not being done due to the press of current activities and generally low profitability in both the vehicular and the materials supplying industries.

4.4.11 Alternate Fuels Combustion

Alternate fuels for transportation engines comprise all nonpetroleum-derived fuels applicable to this sector. The focus of this section is highway vehicles, which consume 75% of the petroleum used in transportation and 38%

of the petroleum consumed nationally. The research opportunities for alternative fuels combustion in industrial engines discussed in Section 5.4.11 may have some applicability to marine and railroad engines, due to their similarity in size and fuel requirements.

As the world demand for petroleum increases over the world supply, the role of alternate fuels is anticipated to become increasingly important. The consensus of opinion in both industry and government is that the need for alternate fuel capability will become significant in the 1990s.

The alternate fuels considered here are alcohols, coal and shale synfuels and distillates, hydrogen, and exotic fuels such as slurries and pulverized solids. The choice of an optimum fuel is affected by several important parameters, such as resource availability, processing requirements, thermal and combustion characteristics, fuel distribution requirements, engine modifications, and environmental and safety requirements. A systems approach is clearly necessary in understanding how each element affects the fuel's attractiveness.

Important economic links exist between the degree of fuel processing and the fuel quality requirements of the engine. For example, converting SRC-II liquid to gasoline would cost more than $13/bbl (Freel 1980). Using less processed fuels enhances the economic competitiveness of alternate fuels with conventional fuels.

Although the need for alternate fuels research has been widely discussed, little has been accomplished because of the sparse quantity of several fuels, notably synfuels. Research opportunities identified a few years ago therefore largely remain.

The potential for substitution of alternate fuels for petroleum is very large on a national scale. Transportation vehicles consume 50% of the petroleum used in the United States. Highway vehicles account for 75% of this, or 15.7 quads (see Table 4.1). As discussed previously, the CONAES panel projects a range of consumption in highway vehicles in 2010 from 7.4 to 21.2 quads. If suitable fuel-engine combinations were developed, alternate fuels could penetrate the entire highway vehicle market.

The primary focus of applied research in alternate fuels should be in determining fundamental combustion characteristics and understanding critical fuel/engine interaction. Applied research could help this technology obtain its potential by providing the capability to burn fuels with reduced processing requirements, and hence, lower costs. Determining fundamental combustion characteristics will enable optimal fuel/engine design without the need for individual fuel/engine pair testing.

The alternate fuels that possess the largest potential for substantial use in the 1990s through continued development are synthetic fuels and distillates from coal and shale and methanol derived from coal. Hydrogen fuels may become widespread in the longer term but face additional barriers of storage and distribution. Although these appear to be the most probable options, other options continue to arise and should be monitored and assessed. Examples of R&D opportunities in these areas are given below.

Coal and Shale Synfuels and Distillates

Both coal and shale are domestically abundant resources and provide an attractive base as alternate fuel sources. Coal liquids appear to be more attractive as a gasoline substitute than shale due to coal's high aromatic content. However, coal liquids suffer from a very low hydrogen content of 5.9% (Ecklund 1980), compared to 14.3% for petroleum and 13.8% for shale. Manufacturing the hydrogen required to upgrade coal is responsible for 60% of the capital investment required for liquefaction (Ecklund 1980). The ash content of coal liquids poses an additional problem and unburned aromatics in the exhaust gas are carcinogenic.

Shale-derived liquids are highly paraffinic and possess a high cetane number that makes this source desirable as diesel and jet fuels. The hydrogen requirements are not as severe as they are for coal, but other problems must be addressed, such as the waxy nature of the liquid at low temperatures and the high sulfur content of minimally processed liquids. These liquids are already in the distillate boiling range appropriate for jet and diesel engines.

To achieve use of fuels permitting a minimal amount of processing, fundamental fuel-engine combustion relationships must be understood. Examples of research activities are listed below.

- Flame speeds and ignition delay need to be determined to aid in engine and fuel design and in modeling emissions.
- Relationships between fuel vaporization and engine performance need to be studied. Viscous fuels inhibit vaporization and increase unburned hdyrocarbons.
- The effects of nitrogen and sulfur compounds on exhaust emissions and engine durability need to be determined. Fuel-bound nitrogen is high in both coal and shale.
- Fuel and engine properties promoting the formation of particulates and PNA hydrocarbons need to be discovered.

Alcohols

In this category methanol from coal appears to be the most promising alternate fuel that will have national availability. Blends of ethanol, methanol, and other oxygenated hydrocarbons with gasoline have been successfully demonstrated and do not appear to require additional applied research.

Neat methanol has the desirable qualities of a high octane number and a 50 to 60% reduction in NO_x emissions (Ecklund 1980). Vantine (1976) reported that fuel economy of methanol in a stratified charge engine may be 70% greater than that of gasoline in a conventional engine. However, for methanol to obtain its potential, problems must be overcome:

- Cold start and warmup drivability problems require further research. Methanol encounters starting problems below about $42^{o}F$. Research might focus on engine design or fuel additives.
- Wear problems need to be understood and mitigated. These problems typically arise in the upper cylinder, bearings, and injectors.
- Efforts to reduce aldehyde emissions are necessary to permit environmental acceptability.

Hydrogen

Hydrogen has potential application in a wide range of engines including spark ignition, diesel, and jet engines. Because hydrogen burns with a high-flame speed, it exhausts little unburned fuel. The CO emissions are essentially nil since the only carbon present is lubricating oil seeping into the chamber. Although combustion heat is high, hydrogen can burn in a very lean mixture, with an equivalence ratio of 0.4-0.5, resulting in a low NO_x level. A primary disadvantage in hydrogen use is that the decreased charge energy reduces the power level compared to conventional engines.

Hydrogen may be an attractive fuel for use in transportation engines. However, before substantial research investments can be justified a hydrogen economy must be shown to be a practical future possibility. Unless hydrogen can be shown to be a possibility in less than the very long-term, hydrogen-related research should probably be kept at a low level just to keep these technologies in a state of readiness.

Exotic Fuels

The necessity of appraising exotic fuels stems from the need to keep informed of all fuels that might significantly substitute for petroleum. Examples include powdered coal, powdered wood, and various slurries such as liquified wood.

Research into coal and shale synfuel combustion in engines is being performed on a very small scale in several organizations. The Southwest Research Institute, Exxon, Gulf Research, Ricardo and Company, General Motors, and the University of Wisconsin are among the organizations investigating combustion characteristics in various engines. Alcohol fuels have received the most extensive attention with various blends commercialized (e.g, gasohol) or ready for fleet testing. The organizations involved include the University of Wisconsin, Santa Clara University, Union Oil, Penn State, Suntech, Inc., the University of Miami, the DOE office in Bartlesville, Oklahoma, the U.S. Army Fuels and Lubricants Research Center, the University of Michigan, and General Motors. Research into hydrogen-fueled vehicles has received government support in several countries, such as Germany, Japan, France, and India, but has experienced limited research in the U.S. U.S. firms include International Harvestor, Exxon, and Billings Energy Research (which performed a $847,000 proprietary study between 1973 and 1975) (TRW 1977). General Motors is currently testing an automotive turbine fueled by powdered coal.

In addition to technical problems, several significant nontechnical issues exist that will affect the use of alternate fuels. Among these considerations are the availability of alternate fuel resources, the relative costs of petroleum and alternate fuels, the fuel distribution requirements, and environmental and safety requirements.

Coal, shale, biomass, and sea water are all domestically plentiful resources. However, access to coal and shale in the west is still an unresolved question. Petroleum's anticipated cost and availability are major uncertainties that may control the viability of alternate fuels' use. Shifts in foreign oil prices can quickly undercut the synthetic fuels market. The production cost of a barrel of Middle Eastern oil is yet approximately $.04/bbl (Thurow 1980); hence, the potential for underselling the current price of over $30/bbl is significant. The U.S. transportation fuel distribution system is very dispersed and most likely is limited to accommodating two basic fuels (Ecklund 1980). The fuel's ability to be handled and metered within this structure will certainly enhance acceptance. A possible avenue of initial penetration is vehicular fleets. Fleets in the U.S. comprise one million autos and three million trucks and possess central fueling facilities. Environmental and safety considerations also pose problems that must be addressed by all combustible fuels. The changing nature of these regulations also induces added uncertainty to fuel's ultimate cost.

Timely availability of alternate fuels will require federal impetus to assure the technology's availability. The private sector will most likely wait until the necessity of the shift is imminent, which may result in significant economic disruption.

The shift to alternate fuels may also be enhanced if the total cost of imported oil is considered. The Institute of Gas Technology assessed the true cost of imports in a study, in which they also included the international trade balance, the effect on world oil prices, dollar leakages, and supply disruption costs. They determined that the actual cost for imports is $50-70/bbl ($9-12/MMBtu) (Seay 1980). In this light, alternate fuels are a bargain.

Although interest in this technology is widespread, the paucity of fuels and funding has limited research to small projects. Research into shale and coal synfuels and distillates is recommended to be pursued for the 1990 time frame and research into hydrogen fuels to be pursued as a long-term possibility.

5.0 INDUSTRY

The industrial sector is the largest of the three major energy end-use sectors. In 1973 industry used 24.4 quads of total energy. If electrical generation losses are accounted for, industrial energy use was 29.6 quads of total primary fuel (Lovins 1977). Of the 24.4 quads, roughly 20 quads were used in the manufacturing sector. The remainder was accounted for by the extractive, construction, and other nonmanufacturing industries.

Table 5.1 shows a breakdown of energy use by fuel type for the top ten energy-consuming industries in the manufacturing sector. These ten industries account for 95% of the energy used in the manufacturing sector. Natural gas is the most prevalent fuel used, followed by oil. However, wide differences in fuel use among and within industries make further generalizations difficult. For example, the stone, clay, and glass industries rely heavily on natural gas to fire their furnaces, while the paper industry uses fuel oil and forest fuels (residual pulping liquors, hogged wood, and bark). Within the primary metals industry, the steel industry obtains approximately three-quarters of its energy from coal, while the aluminum industry relies heavily on electricity and natural gas (Oak Ridge Associated Universities 1980). Fuel use in industry is much more complex than in the other end-use sectors and therefore requires more thorough analysis than buildings or transportation energy use.

To avoid oversimplification of the industrial sector, a slightly different format is used to discuss industry than was used in Chapters 3 and 4 to discuss buildings and transportation. Rather than a single, sector-wide discussion of future energy use and conservation potential, industry-specific discussions for several major industries are presented. This finer perspective allows consideration of the significant differences in energy use among and within industries. Six of the ten industries in Table 5.1 are discussed in detail: Chemicals and Allied Products (SIC 28); Primary Metals (which is divided into Steel and Aluminum) (SIC 33); Paper and Allied Products (SIC 26); Stone, Clay, and Glass (SIC 32); Food and Kindred Products (SIC 20); and Textile Mill Products (SIC 22). These basic materials industries were chosen for detailed analysis because they use large amounts of heat in their processes and are

TABLE 5.1. Energy Use in the Top Ten Energy-Consuming Industries, 1974 (Chiogioji 1979)

SIC	Industry	Energy Use (10^{12} Btu) Coal	Oil	Natural Gas	Electricity	Other	Total
28	Chemicals and Allied Products	322.2	2085.4	2092.6	436.9	274.0	5211.0
33	Primary Metals	2639.2	418.7	1284.3	536.3	-76.1	4802.3
29	Petroleum and Coal Products	5.3	745.3	2154.5	83.7	83.2	3071.9
26	Paper and Allied Products	208.8	576.4	414.3	132.7	891.6	2223.8
32	Stone, Clay, Glass	233.0	125.5	696.3	99.6	146.9	1301.3
20	Food and Kindred Products	75.3	132.3	475.6	126.7	124.8	934.7
34	Fabricated Metal Products	11.1	38.9	208.2	88.4	60.7	407.2
37	Transportation Equipment	47.6	40.5	144.1	97.1	41.1	370.3
35	Machinery, Except Electric	20.1	33.5	164.3	90.7	52.5	361.2
22	Textile Mill Products	22.0	62.7	102.1	91.8	38.1	316.7
	Other	57.5	160.8	372.7	308.0	206.1	1105.5
	Total Manufacturing	3642.1	4420.0	8109.0	2091.9	1842.9	20105.9

generally considered to offer opportunities for significant technological improvements. One of industries not chosen for detailed study, the Petroleum and Coal Products (SIC 29) industry, is considered an energy supply industry and therefore different in orientation than the basic materials industries. The other industries, SIC 34, 37 and 35, are considered fabrication industries and use far fewer heating processes. The industries that are not included in this study are certainly not unimportant from an energy conservation standpoint and should be considered in future studies. However, to provide a consistent focus for this analysis, this study concentrates on the basic materials industries.

Although energy conservation measures should be considered on an industry-specific basis, from a research standpoint many energy conservation technologies are common to several industries. For instance, development of improved heat exchangers or lubricating materials could have energy conservation applications in various industries. Generic industrial conservation technologies such as these should be evaluated in light of their multi-industry applications. To include research opportunities addressing both industry-specific technologies and generic industrial technologies, this chapter discusses industrial energy conservation from both perspectives. Section 5.1 contains capsule discussions of the six major basic materials industries. Section 5.2 identifies a list of generic energy conservation technologies derived from the industry-specific discussions and other sources. A screening process is performed on this list in Section 5.2, and Section 5.3 presents more detailed analyses of the energy conservation potential and possible research opportunities for selected technologies.

5.1 ENERGY CONSERVATION IN SPECIFIC INDUSTRIES

The discussions of the six major 2-digit SIC basic materials industries focus on the following areas: 1) a brief overview of the industry, 2) a review of energy use and conservation potential, 3) a summary of major energy conservation technologies, and 4) where possible, an indication of research opportunities to support these energy conservation technologies. The industries are discussed in descending order of total energy consumption.

5.1.1 Chemicals and Allied Products

The chemical and allied products industry (SIC 28) is classified into 28 4-digit classes by the 1972 Standard Industrial Classification (U.S. Department of Commerce 1976). The industry currently constitutes roughly 8% of total manufacturing sales, while employing 5% of the total labor in manufacturing (Oak Ridge Associated Universities 1980). Industry sales volume steadily increased through the latter part of the 1970s, but dropped off during the early part of 1980 and has remained sluggish since (*Chemical Engineering* 1981a and 1981b).

Today the industry is operating at less than favorable plant-utilization factors. Low plant utilization combined with current high interest rates has resulted in curtailment of capital investments previously planned for 1981. Earlier surveys estimated an increase in capital investment (in nominal terms) of 16.2% in 1981 over 1980. However, current estimates place the growth at about 8.7 percent (Chemical Engineering 1981b).

Table 5.2 gives estimates of the total energy used by SIC 28 for 1972 and 1978 for each of the energy sources used. Energy use by the industry is substantial, amounting to nearly one quarter of all energy used in the manufacturing sector. The numbers in Table 5.2 represent purchased fuels and electricity only and do not exactly match those in Table 5.1, which includes fuels internal to the industry. Table 5.3 breaks down energy use in the

TABLE 5.2. Energy Use by Fuel Type in the Chemicals Industry, 1972 and 1978 (10^{12} Btu) (Oak Ridge Associated Universities 1980)[(a)]

Fuel Type	Total SIC 28 (104 Companies) 1972	1978
Natural Gas	1,631.01	1,237.24
Distillate Fuel Oil	33.08	63.74
Residual Fuel Oil	193.87	268.90
Coal	318.04	296.40
Electric Power	708.75	875.97
Steam	133.43	116.53
Propane	19.06	8.46
LPG	2.81	10.64
Coke	8.52	8.26
Other Gas	336.45	350.75
Other Liquids	52.70	81.01
Other Solids	11.13	16.77
Total	3,448.85	3,334.67

(a) Estimated SIC 28 capacity utilization for 1978 is 80.3%. For base year 1972 it was 83.5%.

TABLE 5.3. Energy Use in the Chemicals Industry by 3-Digit SIC, 1972

SIC	Product	1972 Energy Consumed (10^{12} Btu)	% of Total SIC 28 Energy Consumed
281	Industrial Inorganics	835.62	27.1
282	Plastics and Synthetics	469.70	15.2
283	Drugs	69.21	2.2
284	Soaps, Cleaners, Toilet Goods	62.00	2.0
285	Paints and Allied Products	19.52	0.6
286	Industrial Organic Chemicals	1,279.79	41.5
287	Agricultural Chemicals	231.68	7.5
289	Miscellaneous Chemical Products	119.83	3.9
	Total	3,087.38	100.0

Source: Mannon 1981, as quoted by Oak Ridge Associated Universities 1980.

chemicals and allied products industry into 3-digit SIC industries. This table shows that industrial organic chemicals (SIC 286) and industrial inorganics (SIC 281) account for over 68% of total energy use in the chemicals and allied products industry. More detailed energy consumption data are available from Chiogioji (1979).

As can be inferred from Table 5.1, significant energy conservation has already occurred within the chemicals and allied products industry for the period of 1972 to 1978. DOE established an energy conservation target of 14% for 1980 for SIC 28 as a whole compared to 1972, with a 17% reduction goal after allowance for nondiscretionary use. Industry net performance exceeded the 14% target by December of 1977, and gross performance exceeded the 17% target by June 1978 (Oak Ridge Associated Universities 1980).

Even though energy conservation targets have been met, many opportunities to decrease energy consumption from current levels still exist. For example, basic changes to the process flow scheme for ammonia production have been estimated to cause a 10 to 15% net decrease in energy consumption from today's levels (Mannon 1981). While this is only one case, it seems safe to assume that the full potential for conservation has not yet been exploited by industry.

In a study to develop energy reduction targets for the chemical and allied products industry, Battelle-Columbus Laboratory (1976) tabulated energy conservation options for each of the 4-digit SIC classifications. Several major energy conservation techniques were discussed in the report:

- better control of combustion in boilers and process heaters
- increased maintenance and analysis of use in steam systems
- waste heat recovery from stack gases and process streams
- waste recovery wastes for fuel values
- optimized process controls because of today's higher energy costs.

Also mentioned as basic conservation techniques for most of the industries were improved plant housekeeping and better planning and scheduling of operations. Some of the major options that are specific to each industry and go beyond these basic techniques and result in energy savings are briefly summarized below for each 4-digit SIC industry.

<u>SIC-2812 - Alkalies and Chlorine</u>

- Replacing old plants with more efficient new plants can result in substantial energy savings.

<u>SIC 2813 - Industrial Gases</u>

- More efficient compressors, heat exchangers, and distillation columns can result in energy savings in gas purification, compression, and refrigeration energy savings.

<u>SIC 2816 - Inorganic Pigments</u>

- New products that can be made with less energy but perform identical functions can be developed.
- Dewatering options prior to drying can be improved.

<u>SIC 2819 - Industrial Inorganic Chemicals, N.E.C</u>.

- No significant options are unique to the industry.

<u>SIC 2821 - Plastic Materials, Synthetic Resins and Nonvulcanizable Elastomers</u>

- Research in production methods has resulted in the development of significantly less energy-intensive processes.

SIC 2822 - Synthetic Rubber

- Research in improved production methods, such as nonsolution polymerization processes, holds promise for reducing energy requirements by as much as 50%. The innovations have not been documented, however.
- Improved catalyst selection can save energy.

SIC 2823 - Cellulosic Manmade Fibers

- No options are unique to industry.

SIC 2824 - Synthetic Fibers Except Cellulosic

- No options are unique to industry.

SIC-283 - The Drug Industry

- In the chemical industry energy consumption is small compared to other manufacturing industries. Housekeeping type conservation techniques are most important.

SIC 284 - Soap, Detergents, and Cleaning Preparations, Perfumes, Cosmetics, and Other Toilet Preparations

- No options are unique to industry.

SIC 2851 - Paints, Varnishes, Lacquers, Enamels and Allied Products

- In the chemical industry energy consumption is small compared with other manufacturing industries. Housekeeping type conservation techniques are most important.

SIC 2861 - Gum and Wood Chemicals

- Better control of distillation processes can reduce energy.

SIC 2865 - Cyclic (Coal Tar) Crudes, and Cyclic Intermediates, Dyes, and Organic Pigments and Toners

- No options are unique to industry.

SIC 2869 - Industrial Organic Chemicals, Not Elsewhere Classified

- No options are unique to industry.

SIC 2873 - Nitrogenous Fertilizers

- Ammonia production uses 98% of the energy in this classification, indicating improvements to ammonia manufacturing are of fundamental importance.
- Rapid progress has been made in the last 15 years toward designing ammonia plants that use less energy through more efficient processes.
- Stack gas heat recovery from reformers and cryogenic recovery of hydrogen from purge gas can save energy.
- Nitric acid plants can use hot gas expander and auxiliary steam turbine driven by waste heat to replace electric motor drives.

SIC 2874 - Phosphate Fertilizers

- No option is unique to industry.

SIC 2875 - Fertilizer, Mixing Only

- No option is unique to industry.

SIC 2879 - Agricultural Chemicals

- No option is unique to industry.

SIC 2891 - Adhesives and Sealants

- No option is unique to industry.

SIC 2892 - Explosives

- No option is unique to industry.

SIC 2893 - Printing Ink

- No option is unique to industry.

SIC 2895 - Carbon Black

- No option is unique to industry.

SIC 2899 - Miscellaneous Chemical Products

- No option is unique to industry.

Of the major conservation techniques mentioned in the Battelle-Columbus report (1976), the area of waste heat recovery may have the largest potential savings through applied research in heat exchangers and heat recovery techniques. Other options, such as improved boiler combustion control, and better plant housekeeping, are dependent on engineering development rather than on applied research.

Beyond these incremental technology developments, the area where R&D could have the largest impact on the energy use in the chemicals industry is in process development. Several possibilities exist:

- development of new, more energy-efficient processes
- development of new products that can be produced with little energy and replace more energy-intensive products. For example, future improvements in the hiding power of TiO_2 (an organic pigment) may reduce specific manufacturing energy by 15% (Battelle-Columbus Laboratory 1976)
- development of new catalysts to result in very large energy reductions by the industry.

5.1.2 Primary Metals

Table 5.4 shows a breakdown of energy use in the primary metals (SIC 33) industry by 4-digit SIC. These numbers do not match those in Table 5.1 because internally produced energy is not included in the totals. This table shows that blast furnaces and steel mills (SIC 3312) and primary aluminum (SIC 3334) are the two largest users of energy and account for over 62% of energy use in the primary metals industry. Because of the predominance of these two industries, the discussion of primary metals is divided into two sections. The first section treats the iron and steel industry and the second covers the primary aluminum industry.

5.1.2.1 Iron and Steel

In 1978 raw steel was produced by approximately 80 companies, in 160 plants, and employed 468,000 people (Oak Ridge Associated Universities 1980). Production workers accounted for 75% of the staff and nonproduction personnel

TABLE 5.4. Energy Use in the Primary Metals by 4-Digit SIC, 1976

SIC	Industry Group	Purchased Fuels and Electricity (10^{12} Btu)	Purchased Fuels and Electricity (% of SIC 33 Total)
3312	Blast Furnaces and Steel Mills	1,427.4	60.0
3313	Electrometallurgical Products	54.9	2.3
3315	Steel Wire and Related Products	13.7	0.6
3316	Cold Finishing of Steel Shapes	15.8	0.7
3317	Steel Pipes and Tubes	12.2	0.5
3321	Gray Iron Foundries	104.4	4.4
3322	Malleable Iron Foundries	15.2	0.6
3324	Steel Investment Foundries	3.4	0.1
3325	Steel Foundries, N.E.C.[a]	31.9	1.3
3331	Primary Cooper	69.6	2.9
3332	Primary Lead	13.3	0.6
3333	Primary Zinc	26.4	1.1
3334	Primary Aluminum	297.1	12.5
3339	Primary Nonferrous Metals, N.E.C.	35.7	1.5
3341	Secondary Nonferrous Metals	34.5	1.4
3351	Copper Rolling and Drawing	24.5	1.0
3353	Aluminum Sheet, Plate and Foil	67.6	2.8
3354	Aluminum Extruded Products	19.0	0.8
3355	Aluminum Rolling, Drawing, N.E.C.	8.1	0.3
3356	Nonferrous Rolling, Drawing, N.E.C.	11.4	0.5
3357	Nonferrous Wiredrawing, Insulating	24.3	1.0
3361	Aluminum Foundries	28.2	1.2
3362	Brass, Bronze, Copper Foundries	4.2	0.2
3369	Nonferrous Foundries, N.E.C.	6.6	0.3
3398	Metal Heat Treating	21.1	0.9
3399	Primary Metal Products, N.E.C.	10.1	0.4
	Total for SIC 33[b]	2,380.5	100.0

(a) N.E.C. = Not Elsewhere Classified.
(b) Figures may not sum to totals due to independent rounding.

25%. Iron and steel foundries consisted of 1,300 establishments and employed 226,000 people. The total revenues of iron, steel, and foundry products were $46 billion, at a total production of 124 million tons of raw steel and 16 million tons of iron castings (Oak Ridge Associated Universities 1980).

For several years after World War II the U.S. iron and steel industry was clearly the world's leader. However, as the European and Japanese industries modernized and much of the U.S. equipment simply aged, the industry's position has steadily deteriorated. Between 1956 and 1978 the U.S. fraction of world production of raw steel dropped from 36.8% to 17.5%, while output only increased from 104.5 million tons to 124 million tons (Office of Technology Assessment (OTA) 1980b). Meanwhile, the combined Japanese and European growth rate over that same period was 10 times that of the U.S.

U.S. imports have also grown at roughly 10% per year since the late 1950s. Steel exports in 1978 were only 20% of the steel imports, and iron exports were a mere 6% of iron imports. This economic situation created a combined trade deficit of $6.53 billion (OTA 1980b).

Although the industry has attempted to modernize its facilities, it is still burdened with old facilities that were designed and constructed when energy was cheap and plentiful. A shortage of investment capital, the high cost of borrowed money, difficulties in retrofitting old facilities, and necessary purchases of pollution abatement equipment are among the factors contributing to the industry's declining position.

Raw steel-producing plants can be classified into three general categories: large integrated plants, nonintegrated plants, and specialty shops. Integrated plants normally start with iron ore and coking coal and produce molten pig iron in a blast furnace. This hot metal is then passed through a steelmaking furnace (basic oxygen, open hearth, or electric arc), which produces molten steel that is subsequently cast and formed into the finished product. The capacity of integrated plants is typically 0.9 to 8.2×10^6 ton/yr and captive mines owned by integrated steel firms supply 85% of the domestic ore. Nonintegrated plants typically begin with scrap steel, pig iron, or direct reduced iron and process the material through a steelmaking furnace to the finished product. These plants normally address regional markets and produce 91,000 to 910,000 tons of steel per year. The specialty shops specialize in the production of special products and alloys. These plants usually do not process raw material or engage in iron making. Production typically ranges from 9,000 to 109,000 ton/yr.

Over the past several years the cost of energy has become an increasingly significant element of the total production cost. In 1978 energy represented nearly 20% of the cost of producing steel, while ten years before the cost of energy was only 10%.

Energy use is broken down by process unit and by fuel type and is shown in Figure 5.1 and Table 5.5. Figure 5.1 clearly shows that the blast furnace, accounting for 40% of all the energy used, is by far the major energy user. Heating and annealing, using 15% of the total energy, is the next most energy-consumptive process, and coking is third, consuming 10%.

As Table 5.5 indicates, the primary critical fuels are natural gas and fuel oil, which account for 16.7% and 6.3% of the total fuel requirements, respectively. Electricity supplies another 13.1% of the energy and metallurgical coal currently supplies the bulk of the remaining energy in the form of coke and other byproducts.

Although the future supply of metallurgical coal appears debatable, the aging coking facilities in the U.S. undoubtably will limit coke availability. One third of the coking ovens currently in use are old by industry standards (OTA 1980b) and productive capability has dropped 20% since 1973. Investment in new ovens has been discouraged because of several factors, among which are the high capital costs and regulatory requirements. The continuing decline in capacity and growth in demand has led to the estimate that the U.S. will be importing 20% of its coke by 1985 (OTA 1980b).

General estimates for conservation potential are difficult to cite because each process option is unique. One generic area that has been assessed is waste heat recovery. Typically, two thirds of the input energy is wasted. Approximately 13% of the input energy exists as waste gas; 16% is lost in the cooling water; 13% is left as sensible heat in the residual water (e.g., slag, coke, etc.); and 24% escapes to the ambient environment. NATO has estimated that 40% of this waste heat can be recovered and the United Kingdom places the estimate at 30% (OTA 1980b). The conservation potential of several near and intermediate-term technologies in the steel industry has been estimated by Arthur D. Little, Inc. (1978) and Battelle-Columbus Laboratories (1980).

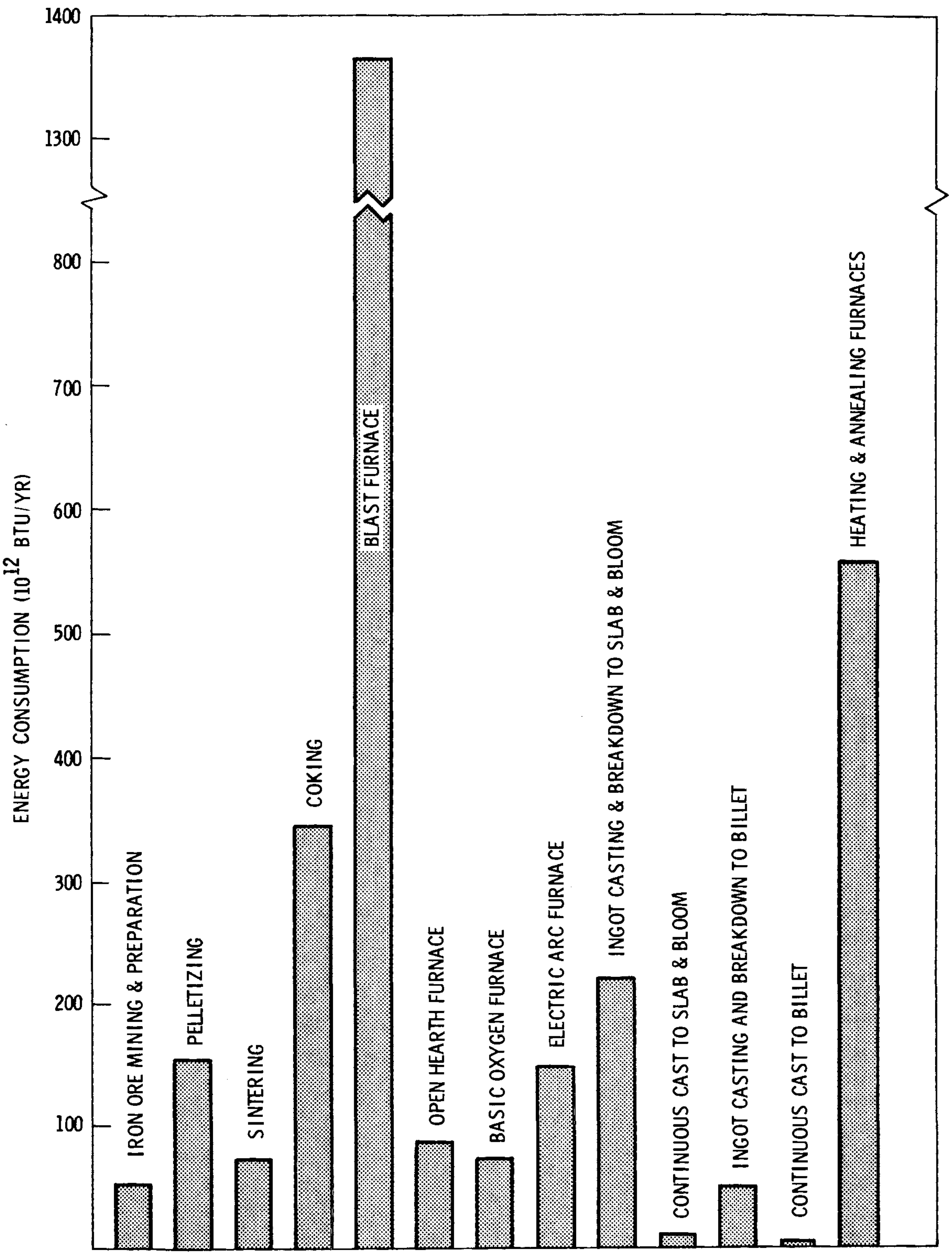

FIGURE 5.1. Estimated U.S. Level-1 Energy Consumption by Major Process Units in 1976 (Arthur D. Little, Inc. 1978)

TABLE 5.5. Energy Consumption by Fuel Type in the Steel Industry, 1976 (Arthur D. Little, Inc. 1978)

Fuel Type	Quantity, 10^{12} Btu	Percent of Total
Fuel Oil	224.0	6.30
Tar and Pitch	39.3	1.11
Liquid Petroleum Gas	3.6	0.10
Natural Gas	595.0	16.74
Coke Oven Gas	435.0	12.24
Blast Furnace Gas	414.0	11.65
Coke	1303.0	36.67
Steam Coal	75.0	2.11
Purchased Electricity	465.0	13.08
Total Energy	3553.9	100.00

Energy conservation opportunities in the steel industry can be divided into three categories: housekeeping measures, evolutionary- or intermediate-term technologies, and long-term revolutionary or radical options.

Housekeeping activities are simply applications of available technology that generally do not require substantial capital investment. Since research can contribute little to this category, it is not discussed here.

Evolutionary- or intermediate-term changes involve switching to newer, more efficient technologies. Many of these technologies have been widely adopted by foreign concerns and must experience similar acceptance in the U.S. if the industry wishes to remain internationally competitive. Recent studies of the iron and steel industry performed for DOE have focused on this category of technologies. Tables 5.6 and 5.7 summarize the major evolutionary ideas that have been considered.

Among the broad number of options with potential for energy conservation and productivity improvement are a few technologies with particular promise: continuous casting and rolling; direct reduction; production of formed coke, external desulfurization, and generic systems for waste heat recovery; high temperature sensing; and computer control.

TABLE 5.6. Energy Conservation Options in the Iron and Steel Industry (Arthur D. Little, Inc. 1978)

Sector	Example of Concepts	Energy Conservation Potential[a]	Comments
Agglomeration	Conversion from natural gas or fuel oil to coal in pelletizing plants	B	Technology established
Grinding of Iron Ore	Improvement in particle classification	B	Small improvements over time
Electric Arc Furnace	Modeling	B	Small improvements over time
Basic Oxygen Furnace	Use of BOF off-gases other than for scrap preheating	B	CO gas collection technology established, but an economic system for use of CO still to be devised
Flue Dusts and Sludges	Recovery of metallic and carbon values	B	An important problem relating to waste disposal
Ladle Preheating	More efficient ladle preheater	B	Logistical and engineering problem
Direct Reduction	Steam coal or lignite based process	A	Conserves metallurgical coal; process development expected to be capital-intensive
Lime Manufacture	Oxygen use in lime kilns; fluid bed process	B	Most applications would be outside of steel industry

(a) A = Potential for national energy conservation of 50-500 x 10^{12} Btu/yr
B = Potential for national energy conservation of 5-50 x 10^{12} Btu/yr

TABLE 5.7. Energy Conservation Technologies in the Steel Industry (Battelle-Columbus Laboratories 1980)

Technology	Estimated Energy Saving, (10^{15} Btu/yr) Total Potential	Probable by 1985 Without Government Programs
Preheat scrap charges to oxygen furnaces	0.37	0.04
High-temperature inspection of slabs	0.20	0.01
Energy management by computers (heirarchical control)	0.20	0.006
Ceramic and metallic high-temp. recuperators	0.14	0.01
Superheating of blast-furnace iron	0.11	0.002
Improved slot forge furnaces	0.10	0.04
Increased recovery of blast-furnace gas	0.06	0.02
Injection of coal into blast furnaces	0.06	0.003
Preheating of ladles	0.055	0.008
Direct use of coal to make pellets	0.35	0.003
Increased use of BOF gas	0.035	0.002
Computer control of blast furnaces	0.025	0.003
Charging preheating coal to coke ovens	0.013	0.002
Ultra-high-power electric melting furnaces	0.014	0.001
Cupola modification to eliminate afterburners	0.01	0.001
Proprietary slab reheating furnaces	0.009	0.001
Computerized power control in arc furnaces	0.0088	0.001
Preheating scrap with electric furnace gas	0.0088	0.001
Electric resistance heating of sheets	0.0075	0.001
Proprietary improved sintering process	0.0043	0.001
Proprietary improved furnace designs	0.0025	0.001
Proprietary batch coil annealing system	0.0005	0.0001
Proprietary scrap preheating	0.0001	0.0001

Continuous casting will most likely be the most important technological change over the next 10 years. In continuous casting molten steel is directly converted to its semifinished form. This single process replaces ingot casting, mold stripping, heating in soaking pits, and primary rolling. Energy consumption is reduced by one-half while the yield is increased from 82% with the conventional method to 96% (Arthur D. Little, Inc. 1978). The annual energy saved has been approximated as 0.2 quad/yr (Arthur D. Little, Inc. 1978). Additional benefits include reduced capital cost per ton of output, increased labor productivity, increased quality of the semi-finished product, reduced pollution, and increased domestic use of scrap (Battelle-Columbus Laboratories 1980).

The use of continuous casting has been growing in the U.S. and currently accounts for the processing of 15% of the nation's steel. However, U.S. use still significantly lags behind the Japanese and European industries, which use this process to produce 50 and 29% of their finished steel, respectively. Further, most of the U.S. firms using continuous casting are nonintegrated. Only 9% of U.S. integrated plants use this technology. If continuous casting could be followed by continuous rolling, thereby eliminating a reheat step, additional energy could be saved. For continuously rolling to attain commercialization, additional research is needed to define methods of controlling steel properties and to assure the cleanliness of the liquid steel.

Iron ore can be converted to sponge iron at temperatures well below its melting point through a technique known as direct reduction. This process replaces the blast furnace and differs from the conventional method by producing a solid, metallized product and by allowing a wide variety of reductants to be used in place of metallurgical coal. Optional reductants include coal without coking, gasified coal, biomass, peat, wood and paper wastes, and municipal and industrial wastes. The primary disadvantage with the direct reduction route is its energy intensiveness. A typical direct reduction/ electric arc furnace uses 56% more energy than the conventional coke oven/blast furnace/basic oxygen furnace process (Arthur D. Little, Inc. 1978). The energy use via direct reduction appears more favorable when the offgases are used to drive a combined-cycle system. The electricity generated is then used to help power the electric arc furnace. Direct reduction can also be coupled with other energy generating systems such as nuclear and MHD. These are much longer-term technologies, but Germany and Japan have already begun work on a nuclear/direct reduction plants, which each hopes to have operating by 2000.

Formed coking is a process through which cheaper noncoking coals can be used to replace metallurgical coals. Increased production of formed coke will allow the substitution of plentiful low-grade coals for less abundant metallurgical coal and will reduce the expected increase in coke imports due to this country's aging coking ovens. Several formed coke processes are under development, including the FMC, the Consol-BNR, Japan's DKS, France's HBNPC, West Germany's Ancip, and the Sapozhnikov in the USSR. Although several pilot plants have been attempted, few have been successful to date.

External desulfurization is another technology that is anticipated to significantly impact the industry in the near future. External desulfurization normally refers to any process in which sulfur is removed from the molten pig iron between the blast furnace and the steelmaking furnace. Developing external desulfurization would extend the domestic supply of coking coal by allowing higher sulfur coke to be used in the blast furnace. Also, external desulfurization would prevent the increase in energy required if the desulfurization had to be performed in the blast furnace. The energy savings are estimated at 0.07 quad/yr (Arthur D. Little, Inc. 1978).

Developments in generic technologies such as waste heat recovery devices, high-temperature sensors, and computer control are also anticipated to significantly enhance energy conservation over the next few years. As mentioned in an earlier section, waste heat recovery could potentially conserve 40% of the energy used. High-temperature recuperators that can operate in corrosive exhaust streams are needed to enhance energy recovery. Similarly, high-temperature sensors, both contact and remote, would tremendously enhance the ability to control steel composition. This increased control naturally lead to the reduced use of raw materials and energy. Improved sensors, an area which is still in its infancy in the industry, would additionally enhance the computer control over the processes.

Other evolutionary technologies that will most likely contribute to energy conservation and process efficiency include coal injection (can displace

0.119 quads/yr of fuel oil), dry coke quenching (can save 0.064 quads/yr), plasma arc melting, blast gasifiers, and improved recycling techniques. Although these intermediate-term improvements are critical for the industry to remain competitive with foreign competition, the best that can be hoped for is parity. To obtain a competitive edge, new technologies must be developed, which leads to the third area of conservation measures, long-term revolutionary research.

Long-term research provides an abundance of possibilities for increasing the efficiency of various steelmaking processes. Among the options currently discussed are direct one-step steelmaking, direct casting of sheet and strip, plasma arc steelmaking, powder metallurgical routes to finished products, and ore-to-powder systems.

Direct steelmaking is the conversion of iron ore to steel in a single reactor system. This process would replace either the coke oven/blast furnace/basic oxygen furnace route or the direct reduction/electric arc furnace combination. Direct steelmaking thus allows reduction, melting, and refining to occur and to be controlled in a single confinement. In addition, direct steelmaking reduces environmental problems and allows the use of various raw materials. The proposed "S" process could offer a 20 to 30% energy savings (Szekely 1980). To successfully employ this technology in the private sector, several problems remain to be solved, including system containment, difficulties in the coexistence of oxidizing and reducing reactions in the same vessel, injection of refractories that can operate continuously, uniformity of the product over time, and ways to increase the steel output.

Direct casting involves the strip casting of material taken directly from the steelmaking furnace. Thus, whereas continuous casting requires hot and cold rolling, direct casting produces the steel strip that is ready for final rolling. Besides eliminating the hot-rolled slab, this technique offers the possibility of developing unique properties. The concept's technical feasibility has been demonstrated, but the process is far from commercialization.

In plasma arc steelmaking a plasma is created in a steelmaking vessel from either an inert gas, argon or nitrogen, or a reactive gas, hydrogen or methane. Fine oxide particles and solid reductant are then fed into the plasma.

Plasmas are currently used for melting and refining but may also assist in reducing the iron ore. As with direct steelmaking, plasma arc technology is environmentally cleaner than current techniques and also allows various raw materials to be used. This technology is anticipated to be very attractive for the melting of finely divided solids such as reduced iron powder and partially reacted iron oxides. Recycling plant wastes and the direct production of alloy steels are additional applications of plasma arc steelmaking.

The high-energy concentration attained through plasma arc steelmaking results in very large power requirements. Therefore, little would be gained in energy savings when this technology is used with normal grades of steel. The promise for plasma arc steelmaking by the year 2000 appears confined to specialty/alloy shops.

Powder metallurgy is currently used to produce several high quality alloys. In the past, the production of normal steel via powder metallurgical routes had been determined to be uneconomical. However, new demands for high-quality steel products with superior mechanical properties, as in transportation, may warrant re-evaluation. By eliminating certain reheating steps, powder metallurgy can be expected to save energy, although the amount has not been documented in the open literature (Szekely 1980).

Ore-to-powder systems replace the atomization of molten steels to powders by a process that does not require melting. One such process involves initial reduction followed by chemical separation and leaching. This process may be attractive from both standpoints of energy conservation and reduced capital cost. In combination with powder metallurgical techniques, the ore-to-powder-to-steel process may offer an appealing option to the conventional steelmaking process.

In addition to these examples of long-term revolutionary process changes, interesting possibilities exist in tailoring the novel steelmaking ideas with cogeneration systems. One such system is the ELRED process in which the off-gases from a prereducing fluidized bed and the offgases from the plasma arc furnace are fed to a power generating unit, which returns electricity to aid in sustaining the furnace. Cogeneration with MHD generators and nuclear sources are also intriguing options. In the MHD coupled system, offgases from the generator could be used for direct reduction while the electricity produced could be used to power the furnace. The thermal energy generated in a nuclear facility could be used to reform methane or gasify low-grade coals for use in direct reduction. Japan and Germany are presently very interested in this option.

Much needs to be done to improve the declining position of the U.S. iron and steel industry. Energy conservation measures should be considered only within the broader frame of overall system efficiency and productivity. Evolutionary improvements as in the use of continuous casting, direct reduction, formed coking, and external desulfurization must be encouraged to regain parity in the international market. Revolutionary developments such as direct steelmaking, direct casting, plasma arc steelmaking, powder metallurgy, and ore-to-powder systems will be necessary in the long term if a competitive edge is ever to be recaptured.

The industry is clearly laden with old equipment in processes that could experience significant energy-efficiency improvements if the out-dated equipment were replaced by state-of-the-art components. Although the industry is typically very well informed about new developments, adopting new technologies is hampered by several factors, including inadequate capital formation and high regulatory compliance costs. The shortage of capital will also limit the R&D level since the industry funds both modernization and research from profits. The Office of Technology Assessment (OTA) estimates that revitalizing the industry through investments in upgrading the plants will require a 50% increase in capital support during the next decade to $3 billion per year (1978 dollars) (OTA 1980b).

Conflicting government policies have also been responsible for hindering industrial growth (OTA 1980b). Examples include the following:

- promoting energy conservation while not allowing the adoption of continuous casting to qualify for the energy investment tax credit
- encouraging the industry to use more scrap, which requires capital investment, without providing realistic capital recovery
- attempting to hold prices down, while using trigger-price mechanisms, which lead to price increases.

To date government-sponsored research has centered around near-term and demonstration projects, such as hot inspection, a blast gasifier, fluidized bed heat treatment, and electric arc furnace studies. U.S. involvement in the International Energy Association has also been in near-term projects such as dry quenching, scrap preheating, and high-temperature heat exchangers and recuperators. Although these near-term efforts are unquestionably important, much more attention needs to be addressed to long-term options. A thorough study of revolutionary technologies is needed to appraise their energy, economic, and environmental characteristics.

5.1.2.2 Primary Aluminum

Presently, primary aluminum production consists of a two-stage process in which 1) aluminum ore (bauxite) is refined into alumina by the Bayer process, and 2) alumina is reduced electrolytically to molten aluminum by the Hall-Heroult smelting process. The aluminum is then ready for further processing and fabrication. As shown in Table 5.8, the most energy-intensive step in the aluminum making process is the electrolytic reduction of alumina to molten metal, which accounts for over 69% of energy use in aluminum production. This discussion, therefore, focuses on reduction of alumina to aluminum. Table 5.9 gives a process breakdown of energy use in the production of aluminum from alumina. This table shows that the predominant fuel in the aluminum industry is electricity, used to power Hall-Heroult reduction cells. Natural gas, used in holding, casting, and melting furnaces, is the next most prevalent fuel.

The United States has 12 primary aluminum producers operating 31 primary aluminum plants. Because of the energy intensiveness of aluminum production, aluminum plants have been located in areas of energy abundance. The majority of U.S. capacity is located in the Pacific Northwest, Gulf Coast, Tennessee Valley Authority areas, Ohio River Basin, and along the St. Lawrence Seaway.

In 1977 domestic aluminum production was over 9 billion pounds. Partly because of the aluminum's applicability to energy conservation (e.g., weight reduction in automobiles), demand for aluminum has been increasing rapidly. Future growth rates of around 5.8% per year are anticipated, compared to past growth rates of 7% per year (Boercker 1978). Concurrent with rising demand, aluminum producers have been faced with increasing prices and decreasing energy

TABLE 5.8. Energy Use in the Aluminum Industry, 1977
(Oak Ridge Associated Universities 1980)

Energy Source	Bauxite	Alumina	Molten Metal	Holding Casting Melting	Mill Products	Other Fabrication	Total	% of Total
Production (10^6 lb)	2,161	12,167	9,077	19,605	14,618	1,195	--	--
Fuel Type								
Natural Gas	71	87,941	16,804	39,638	43,769	3,973	192,651	19.9
Propane and LPG	5	--	443	870	1,767	199	3,284	0.3
Distillate Oil	51	221	1,293	10,260	3,525	197	15,547	1.6
Residual Oil	--	10,200	981	1,268	2,030	59	14,598	1.5
Lube Oil	3	29	144	123	3,740	112	4,151	0.4
Gasoline, Kerosene	10	55	212	101	879	216	1,473	0.2
Petroleum Coke	--	--	58,765	--	--	--	58,765	6.1
Pitch	--	--	17,942	--	--	--	17,942	1.9
Coal (and Miscellaneous)	--	--	1,694	243	3,667	146	5,750	0.6
Electricity - Hydro[a]	--	5	102,959	698	3,058	84	106,804	11.0
Electricity - Thermal[b] (purchased)	208	6,004	332,506	5,003	49,099	4,046	396,866	40.9
Electricity - Thermal[b] (generated)	--	8,677	139,041	723	3,949	--	152,399	15.7
Total	348	113,132	672,853	59,382	115,483	9,032	970,230	100.0
% of Total	--	11.7	69.3	6.1	11.9	0.9	--	--
Btu/lb	161	4,298	74,127	3,029	7,900	75.6	--	--

(a) Converted at a rate of 3,412 Btu/kWh.
(b) Converted at a rate of 10,500 Btu/kWh.

TABLE 5.9. Energy Consumption in Alumina-to-Aluminum Production (10^6 Btu per short ton) (Oak Ridge Associated Universities 1980)

Process	Electrical[(a)] Energy	Fuel Energy
Hall-Heroult electrolysis	53.2	
Ancillary use		12.8
Anode baking		2.6
Cathode manufacture		1.0
Reheat and holding furnace		8.0
Casting		5.0
Pollution control		1.6
Total	53.2	31.0

(a) Converted at 3,412 Btu/kWh.

availability. The price of aluminum has more than doubled in the past decade, with more increases predicted, largely due to higher energy prices. Foreign locations for future aluminum plants offer lower energy prices but run the risks of political instability. However, unless American aluminum producers can adapt to the increasingly expensive energy in the U.S., foreign aluminum production may increasingly displace domestic production. Energy conservation is an important option by which to reduce aluminum producers' vulnerability to high energy prices and preserve the economic viability of the U.S. aluminum industry.

The role of energy conservation in the aluminum industry cannot be evaluated apart from the other important issues facing the industry. Two issues may prove to be of paramount importance in influencing energy use in the aluminum industry: 1) the bauxite cartel and 2) the cost of capital. The U.S. has very little domestic bauxite resources, and therefore imports the bulk of the necessary bauxite. The 11 major bauxite-exporting countries belong to the International Bauxite Association, a cartel formed in 1974 to increase revenues from bauxite operations in member countries. Levies on bauxite production have become the largest element in bauxite cost (Boercker 1978). If bauxite prices rise sufficiently, American aluminum producers will have incentive to develop processes for producing aluminum from domestic aluminum-containing clays, even though these processes are likely to be more energy intensive than the conventional Bayer-Hall-Heroult process. Nonetheless, such processes are a real future possibility and, therefore, must be considered in evaluating future energy alternatives in the aluminum industry.

A second factor influencing the energy decisions of aluminum industry is the cost of capital. Because aluminum plants are extremely capital intensive, aluminum producers have a strong incentive to continue using existing plants. Thus, unless interest rates come down or some form of "scrap-and-build" assistance is available, aluminum producers may be unwilling to replace older, less efficient plants with new, more efficient ones, even if the potential energy savings are substantial. Therefore, a distinction must be drawn between energy conservation technologies that require a new plant to be built and technologies that can be retrofitted to existing plants. Retrofit technologies seem to face far less serious barriers and may therefore find broader application. Revolutionary processes offer very large potential energy and economic benefits but also face very serious risks.

Improving the efficiency of conventional Hall-Heroult aluminum plants is one technology that may realize energy savings. As noted previously, the primary pot, or Hall-Heroult cell, accounts for the bulk of energy consumption in aluminum production. Since 1940 the average electrical energy required by the Hall-Heroult cells has decreased from the 8.0 to 12.0 kWh/lb Al range to the 5.6 to 8.0 range, representing about a 30% increase in energy efficiency. In general, the way to decrease energy use is either by decreasing cell voltage or increasing current efficiency. These two methods have accounted for most of the decrease in energy requirements.

Several methods exist to decrease cell voltage. One method involves reducing the electrolyte's resistivity. However, use of bath additions such as lithium carbonate to reduce resistivity has resulted in resistance decreases of only a few percent. Another method is to control the anode cathode distance by continually repositioning the anode as it is consumed to eliminate any voltage losses. The most important and practicable technique to reduce voltage losses is to reduce current density by increasing the amperage. This increased amperage, in turn, involves increasing cell size. The trend toward larger cells has been apparent both in new plants and in modernizing old plants. Larger cells not only improve energy efficiency, but also decrease labor costs in relation to productive capacity.

Another method to decrease cell voltage is to increase energy efficiency. Viable techniques include thermal insulation to reduce heat losses, magnetic bus design improvements, and improved sidewall and bottom-thermal insulation design. These techniques have decreased heat losses and adverse electromagnetic effects and have resulted in improved current efficiency and cell-lining life. Electrolyte composition changes have included the use of additives such as lithium fluoride and lower NaF/AlF_3 ratios to improve current efficiency and lower the cell voltage. Solid-state rectifiers (silicon diodes) have increased the efficiency of conversion from alternating to direct current. These changes have not been universally applied to all aluminum plants due to differences in design, costs, or other factors. However, the energy-efficiency improvements that have been made to date can generally be attributed to some combination of these changes.

Besides using large cells, cell control is one of the most important features of more modern plants using the Hall-Heroult process. Cell control is a complex subject, but generally, the problem concerns current efficiency. Negative factors include an anode effect when the alumina content of the cryolite electrolyte falls too low. In modern plants computer monitoring can provide a signal to increase the amount of alumina in the cell. Another area is the control of anode height to break up CO_2 bubbles, which interact with the molten aluminum and reduce current efficiency.

Of some interest from an energy conservation perspective is the Sumitomo process, a variant on the Soderberg anode type. This process is a retrofit on the vertical stud Soderberg and involves a change in electrode composition and a different hood system. While this conversion is usually done for environmental reasons, some indications show that energy consumption can be reduced by as much as 10% (Bosworth 1978).

If only the measures suggested above are considered, further energy efficiency increases seem to be limited in present Hall-Heroult cells. One reason for this limit is that decreasing current density in cells results in less aluminum produced per unit of cell and increased size of the potline building, which in turn results in higher capital costs per ton of capacity and a slower return on investment. The point has probably been reached where lowering current density will no longer offset increased capital costs in decreased energy costs, even though energy costs continue to rise (Beck 1977). Also, increasing cell size beyond about 225 KA can adversely affect voltage stability, current efficiency, and cell lining life because of large electromagnetic effects and heat dissipation problems.

Despite these problems with further energy improvements, potential changes exist that could achieve greater energy efficiency in conventional Hall-Heroult cells. One potential change would be the use of graphite cathode blocks in conventional cells to achieve voltage reductions. Graphite cathode blocks could achieve a 2 to 4% reduction in energy use over the most efficient cell in use today (Beck 1977). Also, a very low NaF/AlF_3 ratio, high LiF, and low temperature electrolyte could achieve a 3 to 5% energy savings by reducing voltage in present potlines. A third retrofit that offers larger energy savings is the use of titanium diboride ($TiBr_2$) cathodes. A $TiBr_2$ cathode is dimensionally stable under electromagnetic forces, electrolyte convection, anode gas evolution from the interelectrode space, anode changing, or other cell operations. The anode to cathode distance can be much less than in a conventional cell without causing severe voltage instability and loss of current (Beck 1977). This $TiBr_2$ cathode characteristic offers the potential for cell size increases, energy-efficiency improvements of 6 to 15%, longer cell-lining life, and greater productivity per unit cell size. However, a cell life between two and three years is estimated to be necessary to justify the installation of $TiBr_2$ cathodes. While laboratory experiments suggest that a life of 7 to 8 years is possible, in practice no one has demonstrated a sufficiently long life to justify the risk of retrofitting several production cells (Arthur D. Little, Inc. 1979).

A straightforward energy conservation technique for the Hall-Heroult cells would be use of recuperators for recovering heat from the potline itself. However, high temperatures and dirty environments present serious obstacles to this option.

A final potline retrofit that could be used to increase energy efficiency is the installation of permanent or nonconsumable anodes in the Hall-Heroult cell. This installation would eliminate the need for an anode prebake plant. An overall efficiency improvement of 8 to 10% might be achieved if a suitable material were found for a permanent anode (Arthur D. Little, Inc. 1979). However, despite ongoing research, many technical problems remain with permanent anodes in addition to the selection of an appropriate material. If a suitable anode is developed, however, no certainty exists that it will be amenable for use as a retrofit in existing cells.

Energy conservation could be achieved in the aluminum industry through other means than retrofits to the conventional aluminum plant. One possibility is increased recycling. Most aluminum companies already encourage recycling because recycled aluminum requires only 5 to 10% of the energy needed for primary production of aluminum from bauxite (Boercker 1978). However, in the U.S. only an estimated 20% of the aluminum used in industrial or customer end product is ever recycled as scrap (Washington Public Interest Research Group 1978), partly because the purity of secondary aluminum is frequently lower than primary. Thus, recycled aluminum may not be applicable to some uses without some purification in secondary smelters. Even with purification, secondary aluminum is much less energy intensive than primary aluminum.

A brief outline of the technologies that offer potential for reducing energy use in conventional Hall-Heroult aluminum plants is presented in Table 5.10. For some of these technologies, engineering development should be sufficient to facilitate application. For others, however, additional applied research is needed. In particular, areas requiring research are materials problems in $TiBr_2$ cathodes, permanent anodes and graphite cathode blocks, durable high-temperature insulating materials for insulating pots and furnaces, high-temperature heat recuperators for potline heat recovery, and advanced purification methods to facilitate greater use of recycling.

In the longer term, research could make alternatives to the Bayer-Hall-Heroult process practicable. Table 5.11 summarizes the major alternative processes that have been proposed to the Hall-Heroult smelting process as evaluated in a study by Arthur D. Little (1979). With the exception of the

TABLE 5.10. Energy Conservation Retrofits in a Hall-Heroult Aluminum Smelter

1. Pot (primary)

   Increased Cell Size
   Increased Thermal Insulation
   Mechanization
   Computerized Process Control
   Electrolyte Changes (low temperature, low NaF/AIF ratio, lithium and sodium salt addition)
   Bus Design Improvements
   Solid State Rectifiers
   Graphite Cathode Blocks
   Titanium Diboride Cathodes
   Permanent Anodes
   Potline Heat Recovery

2. Casting Furnaces

   Heat Recuperators
   Automatic Pressure Control
   Fuel Changes

3. Heat Treat Furnaces

   Heat Recuperators
   Direct Firing Instead of Radiant Tube
   Fuel Changes

4. Anode Bake Plant

   Heat Recuperators

5. Other Energy Conservation Measures

   Increased Use of Recycling
   Changes in Pollution Control Equipment

Alcoa Smelting Process, all of these alternative processes will require large amounts of research to become realistic options. The Alcoa process is proprietary and is therefore not a viable target for federal research support. The process that offers the most long-term potential according to the A. D. Little study (1979) is direct carbothermic reduction of aluminum-silicon (Al-Si) alloys. Basic studies of the Al-O-Si-C system, leading to a practical demonstration of thermal reduction of bauxite to an Al-Si alloy, are recommended. The following are other recommended research topics relating to the development of alternative aluminum production processes:

TABLE 5.11. Alternative Processes for Primary Production of Aluminum (Arthur D. Little, Inc. 1979)

Process	Description	Electrical Energy Consumed kWh/lb	Thermal Energy Equivalent 10^6 Btu/ton	Other Thermal Energy Consumption 10^6 Btu/ton	Total Energy 10^6 Btu/ton	Comments
Hall-Heroult (HH)	Electrolysis of Al_2O_3 in Na_3AlF_6 melt at 960°C in 50-200 KA cells with consumable carbon anode, aluminum pool cathode	6.0-8.0	125-165	25[a]	150-190	Long-established technology, uniquely used world wide in large-scale aluminum production. High electrical energy demand may be reduced by 20-25% with TiB_2 cathodes and permanent anodes-subjects of current research, which should be intensified and accelerated.
Alcoa Smelting Process (ASP)	Electrolysis of $AlCl_3$ in LiCl. NaCl melt at 700°C with multicell bipolar stack of graphite electrodes-anode not consumed	4.5	95	35	130	Advantage of lower electrical energy demand than HH, disadvantage that high purity $AlCl_3$ needed. Economically competitive operation not yet demonstrated publicly. Proprietary process so no action recommended.
Direct Carbo-Thermic Reduction to Aluminum	Arc furnace reduction of alumina with petroleum coke	8.0-14.0	165-290		165-290	Very high temperature needed (∿2010°C) reduction process is complicated by the formation of Al_4C_3 and Al_4O_4C, volatility of Al and AlO and back reaction of Al and CO reform Al_2O_3.
Direct Carbo-Thermic Reduction to Al-Si Alloy	Oxygen blown blast furnace type operation reducing bauxite with petroleum coke	--	--	70	70	Thermal reduction to a commercially useful alloy is very attractive. Al-Si-O-C system should be vigorously studied and practical problems of large-scale operation should be actively considered.
Subchloride or Gross Process	Prereduction of bauxite in electric furnace followed by exposure to $AlCl_3$ vapor which selectively removes aluminum metal as AlCl. Subsequent cooling produces aluminum according to $3AlCl \rightarrow 2Al + AlCl_3$	8.6	180	--	180	Very extensively studied by Alcan, who concluded that it was more electrically energy intensive than HH. Might be feasible if the bauxite were reduced in an oxygen blown furnace. This aspect should be examined.
	Prereduction in blast furnace	2.8	60	60	120	

(a) As fuel and consumable materials in anode fabrication.

TABLE 5.11. (contd)

Process	Description	Electrical Energy Consumed kWh/lb	Thermal Energy Equivalent 10^6 Btu/ton	Other Thermal Energy Consumption 10^6 Btu/ton	Total Energy 10^6 Btu/ton	Comments
Disproportionation of Aluminum Sulfide (Al_2S)	Reaction of Al_2O_3 with recycled Al_2S_3 in the presence of C gives Al_2S. Subsequent cooling produces Al according to $3Al_2S \rightarrow Al_2S_3 + 4Al$	10	210	--	210	Technically a difficult process with both low-pressure and high-temperature operation. Due to significant solubility, contamination of the aluminum with sulfide is very likely.
Nitride Intermediate	Formation of the nitride according to $Al_2O_3 + 3C + N_2 \rightarrow 2AlN + 3CO$ in an induction furnace. Nitride decomposed under vacuum to give aluminum	NA			NA	Batch process, energy intensive, contamination with carbonitride is difficult to avoid.
Sulfide Electrolysis	Formation of Al_2S_3 followed by electrolysis in a fluoride or chloride fused salt bath to give aluminum and sulfur	5.0-6.0	100-125		100-125	This approach is sufficiently attractive, in view of its low electrical energy requirements, to warrant experimental studies to better define the uncertainties in the chemistry. These uncertainties include the means to manufacture Al_2S_3 in high yield and the effect of soluble monovalent aluminum sulfur complexes that are formed at the cathode and oxidized at the anode on the current efficiency.
Nitride Electrolysis	Electrolysis of AlN as Li_3N. AlN dissolved in cryolite at 727°C	3.6	75	60	135	Low-energy process even if AlN made by reaction of $AlCl_3$ with NH_3, because of low decomposition voltage (0.79V) for AlN. Bench scale demonstration only--chemistry not understood.
Monochloride Process	Aluminum is extracted from bauxite with aluminum chloride at 1800°C	6.5	135		135	Laboratory demonstration only, on a large-scale electrical energy requirement might be expected to be similar to the Gross process, i.e., slightly greater than the HH process.
Toth Process	Reduction of aluminum chloride with manganese metal. Manganese chloride is converted to the oxide then reduced to the metal in a blast furnace	10-12	210-250	80	290-330	Manganese oxide cannot be effectively reduced in a blast furnace, so that the process as specified would not operate satisfactorily. Prospects exist for electrolytic regeneration of the manganese at an energy requirement of 3.5-4.0 kWhr/lb Mn (10.5-12.0 kWhr/lb Al)

- the kinetics of the carbothermic reduction of alumina and bauxite
- the manufacture of aluminum sulfide from natural ores and the subsequent electrolysis of the sulfide
- the prospects for the electrolysis of aluminum nitride.

5.1.3 Pulp and Paper

The paper and allied products industry (SIC 26), using 1.3 quads of purchased fuels and electricity in 1977, was the third largest energy-consuming industry (U.S. Department of Commerce 1976). This total does not include hogged wood, spent liquor and other internally produced fuels. Total energy consumption for the industry including these fuels is estimated at 2.16 quads (DOE 1978b). Of this total, over 81% is consumed in paper mills and paperboard mills (U.S. Department of Commerce 1976). In 1977, 29.9 x 10^6 tons of paper and 32.5 x 10^6 tons of paperboard were produced in the U.S. (Fam and Judd 1980).

To understand how energy could be conserved in the paper industry, energy use in the industry should be examined. Figure 5.2 diagrams energy use in the pulp, paper, and boardmaking industries. This figure shows that substantial amounts of oil and gas are used to produce thermal energy. Over 90% of the total energy consumed goes into steam generation and its accompanying losses. More detailed information on energy use in the paper industry can be found in Oak Ridge Associated Universities (1980), U.S. Department of Commerce (1976), DOE (1978b), and Battelle-Columbus Laboratories (1975a).

The thermodynamic minimum amount of energy required by the paper industry is essentially zero (Ross and Williams 1977), partly because the difference in the energy content of the wood inputs and the paper outputs is theoretically sufficient to power the papermaking process. To actually reduce fuel consumption to zero is not technologically feasible at present, nor would it necessarily ever become economically realistic. However, because paper thermodynamically could be produced with very little energy, significant energy savings are possible through long-term technological improvements and fundamental research into the basic papermaking process.

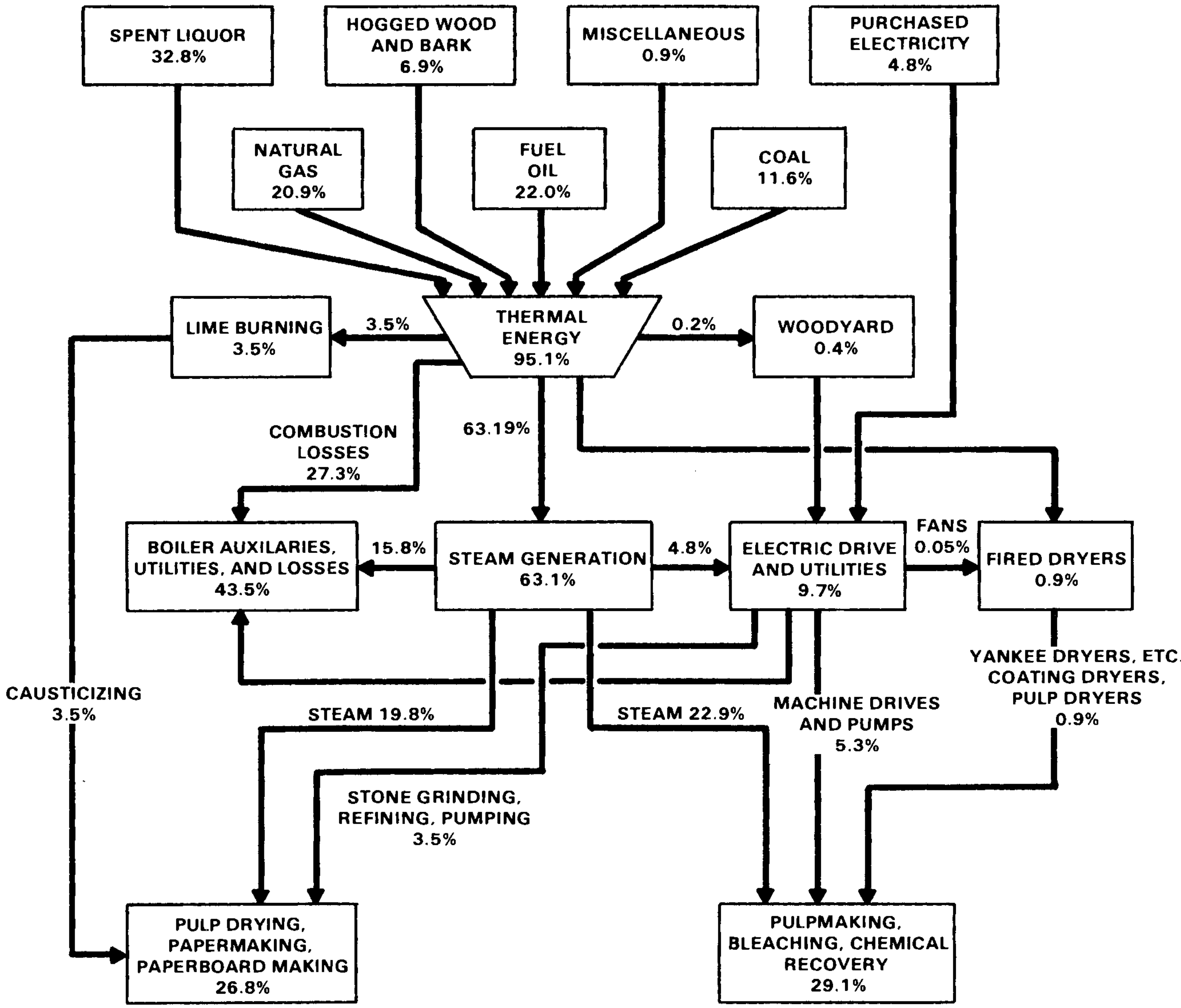

FIGURE 5.2. Estimated Energy Distribution for the Pulp, Paper, and Boardmaking Industries as Percentages of Total Fuel Inputs (2.16 quads) (Oak Ridge Associated Universities 1980)

In the shorter term, the paper industry is most likely to achieve energy conservation through measures that reduce the amount of energy used in steam production. Cogeneration, improved heat exchangers, and heat pumps are promising technologies for this application. Additional details concerning specific energy conservation technologies for the paper industry are presented in a report by Resource Planning Associates (1980). This report estimates that by 1990, advanced air/fuel ratio controls could save 8 x 10^{12} Btu; heat recovery from dryers could save 18 x 10^{12} Btu; and an extended nip press could save 12 x 10^{12} Btu. These estimates of conservation potential were made recognizing the limitations to market penetration of these technologies (Resource Planning Associates 1980).

Table 5.12 lists energy conservation technologies that offer possible areas for applied research. Many of these technologies are currently being addressed, at least in part, in current research programs. However, basic problems still must be resolved before the technologies can be implemented in the paper industry to save energy. Some of these energy conservation technologies may therefore provide fruitful areas for federal research support.

Applied research could promote energy conservation by developing, improving, and reducing the cost of the technologies listed in Table 5.12. Because of steam generation's predominance in the paper industry, research that addresses that basic area is particularly important from an energy conservation perspective. A 30% reduction in energy use is considered technologically feasible given appropriate research support (Chiogioji 1979).

To effectively determine the specific areas where government support of applied R&D relating to the paper industry is warranted, efforts must be made not to duplicate or displace research being addressed by industry. In 1978, over $250 million was spent on R&D in the paper industry. Of this total, approximately 65% came from three companies: Weyerhauser, Scott, and Kimberly-Clark (DOE 1980d). Therefore, any federal research efforts must be coordinated with the corporate research programs of these companies.

5.1.4 Stone, Clay, Glass

The ceramics industry (stone, clay and glass products), SIC 32, consumed over 1.22 quads in 1976. Energy statistics for SIC 32 are summarized in

TABLE 5.12. Paper Industry Energy Conservation Technologies

Technologies	Comments
Inexpensive Heat Exchangers (plastic)	Allow broader use of heat recovery
Airless Dryers	---
Reduced Drying Energy Requirement	---
Press Modeling	---
Mach Nozzle Drying	Used in felt drying
High-Consistency Forming	Much work needed
Improved Drying Efficiency	15% reduction possible, would save 0.09 quads/year
Microwave Drying	---
Hydropyrolysis	Alternative to Tomlinsen Kraft recovery boiler, reduces black liquor to usable wastes
Freeze Crystalization of Black Liquor	---
Radiant Recuperators	---
Optimized Energy Inventory	Redesign plant to include more heat recovery and energy cascading

Table 5.13. The more energy-consumptive processes, dominated by thermal processing (calcining, melting, drying, burning, heat treating), are summarized in Table 5.14. Of the major energy-consuming processes listed, some 825 x 10^{12} Btu or 83% of the energy consumption, was used in thermal processing (furnace heating) in 1976. The remainder of the energy was used in forming operations, crushing and grinding, space heating and cooling, material handling, etc.

Because so much of the energy is used in furnaces of various types, reduction of heat loss from furnaces by adding insulation and sealing leaks, and waste heat recovery are the major conservation actions available to the ceramics industry. Both actions are being taken by the ceramics industry as

TABLE 5.13. Energy Use in the Stone, Clay, and Glass Industry (SIC 32) (Oak Ridge Associated Universities 1980)

SIC Code	Industry Group	1976 Consumption of Purchased Fuels and Electricity (10^{12} Btu)	(% of SIC Total)	1976 Value of Shipments (10^6 $)	10^6 Btu/ 10^3 $ of Shipment	Temperature Range of Process (°F)
3211	Flat glass	53.5	4.4	1,006.3	53.2	
3221	Glass containers	147.2	12.1	3,047.0	48.3	
3229	Pressed and blown glass, n.e.c.[(a)]	67.7	5.6	1,505.6	45.0	
3231	Products of purchased glass	17.3	1.4	1,336.1	12.9	
3241	Cement, hydraulic	434.4	35.6	2,334.3	186.1	
3251	Brick and structural clay tile	57.2	4.7	519.0	110.2	2,000-2,100
3253	Ceramic wall and floor tile	7.1	0.6	210.6	33.7	1,950-2,200
3255	Clay refractories	23.1	1.9	500.2	46.2	1,900-3,000
3259	Structural clay products, n.e.c.	16.6	1.4	181.0	91.7	1,750-2,400
3261	Vitreous plumbing fixtures	8.3	0.7	295.4	28.1	2,160
3262	Vitreous china food utensils	2.4	0.2	107.0	22.4	1,400-2,400
3263	Fine earthenware food utensils	1.3	0.1	101.2	12.8	1,050-2,250
3264	Porcelain electrical supplies	5.7	0.5	342.7	16.6	2,500-2,650
3269	Pottery products, n.e.c.	5.3	0.4	217.4	24.4	1,600-3,300
3271	Concrete block and brick	17.2	1.4	1,015.8	16.9	165-350
3272	Concrete products, n.e.c.	20.4	1.7	2,400.7	8.5	--
3273	Ready-mixed concrete	49.9	4.1	4,974.2	10.0	--
3274	Lime	94.3	7.7	414.2	227.7	1,800-2,400
3275	Gypsum products	41.0	3.4	600.6	68.3	210-305
3281	Cut stone and stone products	4.2	0.3	375.9	11.2	no firing
3291	Abrasive products	10.6	0.9	1,222.2	8.7	5,000-6,000
3292	Asbestos products	10.7	0.9	900.1	11.9	--
3293	Gaskets, packaging, sealing devices	5.6	0.5	842.2	6.6	highly variable
3295	Minerals, ground or treated	38.5	3.2	660.0	58.3	1,400-3,200
3296	Mineral wool	53.0	4.3	1,145.5	46.3	1,400-1,800
3297	Nonclay refractories	19.3	1.6	564.9	34.2	0-5,000
3299	Nonmetal, mineral products, n.e.c.	7.8	0.6	253.9	30.7	
	Total or average, SIC 32	1,219.6	100.0	30,635.2	39.8	

(a) n.e.c. = Not elsewhere classified.

TABLE 5.14. Major Energy Uses in the Ceramics Industry (SIC 32), 1976 (Oak Ridge Associated Universities 1980)

SIC	Industry	Energy Use (10^{12} Btu)	
3241	Cement, Hydraulic		433
	Clinker Burning	348	
	Raw Material and Clinker Milling	48	
3211,21,29	Glass		269
	Melting and Firing	227	
	Forming	42	
3274	Lime		94
	Calcination	90	
3251,3,5,9	Clay Products		104
	Drying and Firing	99	
3275	Gypsum		41
	Calcining	15[a]	
	Drying	23[a]	
3296	Mineral Wool		53
	Melting	20[a]	
	Fiberizing	12[a]	
	Curing	10[a]	
Total for Above Industries			944
Total for Thermal Processing		825 (83% of 944)	
Total for All SIC 32 Industries			1220

(a) Estimated from process analyses by Drexel University (1979).

increased fuel prices and equipment replacement needs make it economical to do so. For example, betweeen 1972 and 1976, typical decreases in the energy intensiveness (Btu/ton of product) of the ceramic industry were around 3% for the lime industry, 6% for cement, 17% for brick and 9 to 21% for glass. These conservation measures resulted largely from housekeeping measures and equipment modernization. These efficiency gains reasonably can be expected to continue for some time as older equipment (typically long lived) is replaced by more energy-efficient modern equipment. More energy-efficient processing equipment exists, but may not immediately be installed because of high investment costs. Applied R&D may be able to reduce the cost of some types of energy-efficient equipment and thereby encourage their use.

In the longer term, applied research may lead to new energy-efficient processes. For example, the fluidized bed process replaced the rotary kiln in cement production at a fuel savings of 33% (Arthur D. Little, Inc. 1976b). Applied research on basic scientific and engineering principles might lead to entirely new processes that would be less energy and capital intensive. This cursory analysis did not uncover any innovative basic processes requiring research. Presumably, such ideas would come from research by individuals having an active interest in a specific industry. When offered, these ideas would be excellent candidates for government funded R&D. The profit squeeze in these industries will tend to prevent reinvestment in high-risk R&D.

The ceramics industries are not highly dependent on oil. Some 80% of the energy used is from coal and natural gas. Approximately 10 to 13% is from oil and 7% is from electricity (see Table 5.15). The industries tend to use natural gas for its clean burning qualities. Coal can be used where the product will tolerate the products of combustion, notably, cement and lime.

The following brief discussions of energy conservation technologies in the four major industries in SIC 32, cement, glass, lime, and clay, illustrate the above points and are based upon a more detailed, well-referenced summary given in the Oak Ridge Industrial Energy Use Data Book (1980). Table 5.16 briefly summarizes the major energy conservation measures that offer research opportunities in those four industries.

TABLE 5.15. Energy Consumption by Fuel Type for Major SIC 32 Industries, 1976 (Lovins 1977)

SIC	Total (10^{12} Btu)	Coal (10^{12} Btu)	Oil	Natural Gas	Electricity
3241 Cement	433	225	36	133	31
3211, 21, 29 Glass	269	0-8[a]	38-46[a]	199	26
3274 Lime	94	52	10	27	3
3251, 3, 5, 9 Clay	104	0-23[a]	9-23[a]	76	5
Total	900	277-308[a]	93-115[a]	435	65
Percent	100%	31-34%	10-13%	48%	7%

(a) Possible ranges given when exact figures were withheld to avoid disclosing figures from individual companies.

Cement

Increasing fuel prices have prompted some significant changes in the cement industry. For example, the wet process, in which large amounts of energy are used to evaporate water from the slurry being calcined, is being replaced by the more energy-efficient dry process. Also, the cement industry has made a dramatic shift to coal and coke, reducing its dependence on oil and gas. Between 1972 and 1978 coal use increased 61%, while residual oil and gas use declined by 36 and 61%, respectively. Other changes, such as increased waste heat recovery, upgraded kiln chain systems, and improved housekeeping, have contributed to increased energy efficiency in the industry. Such modifications can be expected to further increase energy efficiency as prices continue to rise in the future.

In the longer term, process redesign and incremental improvements in technology offer the potential for even greater energy savings. Europe and Japan have introduced notable changes in kiln technology, such as advanced preheater

TABLE 5.16. Summary of Energy Conservation Measures in the Ceramic Industry

Cement

Coal-Fired Flash Calcination
Fluidized Bed Clinker Burning
Improved Heat Recovery from Kiln
Faster Kiln Rotation
Improved Kiln Insulation
Advanced Grinding Technology
Increased Use of Non-Energy Intensive Materials in Final Cement Product

Glass

Batch Preheating
Oxygen Enrichment of Combustion Air
Submerged Combustion
Direct Firing with Coal
Coal-Fired Hot Gas Generation
Coal Gasification
Use of Natural Soda Ash
Heat Source Located at Top of Batch
Recycle of Glass Wastes as Cullet
Use of Returnable Containers

Lime

Advanced Kilns
Sensible Heat Recovery from Kiln Products

Clay

Alternative Fuel Use
- coal (pulverized, producer gas)
- biomass

Kiln Modernization
- increased insulation
- recirculation of kiln gases
- high velocity burners
- heated combustion air

Systems Controls
- fuel/air ratio
- faster firing schedules
- optimum ware setting

systems and flash calcination. Additional technologies in which applied research could improve kiln efficiency include coal-fired flash calcination (present systems use oil), fluidized-bed clinker burning, improved heat recovery from the kiln, faster kiln rotation, and improved kiln insulation (presently 10% of the heat in a kiln is lost through the walls) (Arthur D. Little, Inc. 1976b). Another energy-saving technology for the cement industry is advanced grinding technologies, such as air classifiers that use kiln exit gases in grinding raw materials. Finally, the energy efficiency of producing cement could be improved by the use of nonenergy intensive materials, such as pozzolans, to blend into the final cement product.

Glass

Two relatively recent innovations have contributed to reduced energy use in the glass industry: 1) natural soda ash is replacing synthetic soda ash (potential savings 45 x 10^{12} Btu per year), and 2) the float glass process for making flat glass, which uses 50% less energy while increasing production by several times, is finding increased application. In addition, the regenerative furnaces in which 90% of all glass is melted in the U.S. are being improved as they are rebuilt. Electric furnaces are 65 to 80% efficient (22 to 27% efficient based on fuel equivalent) as opposed to the 15 to 20% efficiency of gas-fired regenerative furnaces.

Further developments could further reduce energy use in the glass industry. Batch preheating could potentially save 15 to 25% of the energy used by glass furnaces. Oxygen enrichment of combustion air is also a potential fuel saver. Submerged combustion could save 50% of glass furnace fuel, but research is needed to solve the problem of bubble formation in the glass. Use of coal in direct firing, hot gas generation, or in gasified form offers the potential of reducing oil and gas usage. Use of natural soda ash in manufacture of glass containers would eliminate the need for energy-intensive production of synthetic Na_2CO_3. Research into the possible reaction of the refractory lining of the furnace and the molten glass could lead to furnaces with the heating flame located at the bottom of the batch rather than at the top. Current furnaces use top-located flames to avoid this reaction and have lower thermal efficiencies as a result. Finally, recycling of glass wastes as cullet and increasing use of returnable glass bottles may offer significant energy savings.

Lime

In lime production the calcination step uses 90 to 95% of the energy. Thus, the greatest impact on energy efficiency would come from improvements in this step. The industry has already begun to shift from natural gas to coal. In 1977 slightly more than 59% of fossil energy used was from coal. Smaller and less efficient lime kilns have gradually been replaced with larger and more efficient ones, resulting in fuel savings of up to 40%. By 1972 most of these kilns were replaced. The lime industry has also saved energy by using internal refractory elements to improve heat transfer in both the kilns and preheaters.

Additional energy-efficiency improvements are possible through new technology development. Two possible areas are the development of advanced, high-efficiency kilns that can produce the necessary product quality, and sensible heat recovery from the kiln products. Recovery of sensible heat from the hot $CaCO_3$ could reduce energy consumption by 75,000 Btu per ton.

Clay

Nearly all energy used in manufacturing brick and structural clay products is used in the firing-drying process. Waste heat from firing is commonly used for drying. As shown in Table 5.15, natural gas dominates energy use in the clay industry. Thus, use of alternative fuels is a potentially important conservation option for this industry. Coal could be used in either pulverized form or to make producer gas. Biomass is also a possible fuel source. At least one company is already using sawdust as its primary fuel source (Drexel University 1979). Modernizing and improving the kilns by increased insulation recirculation of kiln gases, high velocity burners, and heated combustion air offer significant energy savings. Improved systems controls to regulate more precisely the fuel/air ratios in firing and to allow firing schedules timed for energy efficiency and optimum ware setting also offer potential energy-efficiency increases. Leak plugging and increased waste heat use are other energy conservation options available to the clay industry.

Table 5.16 presents a summary of the above energy conservation measures for the cement, glass, lime, and clay industries. Although the energy efficiency of the ceramics industry has improved significantly in recent years and will probably continue to do so in the future, R&D is still needed to augment energy conservation efforts in the industry. Applied research could support the development of fundamentally different basic processes for producing ceramic materials. Although no such processes were identified in this brief industry overview, they are certainly possibilities and should be considered for research funding. Applied R&D could also support the development of modifications to existing processes, such as flash calcination of cement, submerged combustion of glass, and improved kilns. A specific research opportunity is the investigation of the possible reaction of molten glass with the refractory lining to develop furnaces with the heating flame located beneath the batch rather than on top. Because energy is predominantly used in furnaces in the ceramics industry, applied research into improved heat transfer techniques, heat exchangers, and insulating materials offers subtantial application to energy conservation in the ceramics industry by improving furnace efficiency.

5.1.5 Food and Kindred Products

Using 937.5 x 10^{12} Btu, food and kindred products (SIC 20) was ranked by the Census Bureau as the sixth largest consumer of energy in the manufacturing division in 1976 (Oak Ridge Associated Universities 1980). Table 5.17 shows the energy use by the ten largest users of energy in SIC 20. These ten industries account for about 56% of the energy use in the food industry. Meat packers and fluid milk processors use large amounts of energy primarily because they process large volumes of output. Wet corn milling, beet sugar, and cane sugar refineries are energy-intensive industries. Wide variations in energy consumption per unit product occur within individual food processing industries due to plant size, plant design, type of process, and age of boilers.

Table 5.18 shows a breakdown of energy use by fuel type of the three-digit SIC categories in the food industry. Although several entries are missing from this table to avoid disclosing company-specific data, the table gives an idea of the relative degree to which the various fuels are used. Natural gas is the most prevalent fuel used in the industry, followed by coal and electricity. Most of the fossil fuels used in the food industry are for process heat. Smaller amounts are used for space heating, refrigeration, and on-site electric power generation. Most of the process heat is used at temperatures less than 350°F (Battelle-Columbus Laboratories and Pacific Northwest Laboratory 1977).

TABLE 5.17. Energy Use in the Ten Largest Energy-Consuming Industries in SIC 20, 1976 (Oak Ridge Associated Universities 1980)

SIC	Industry	Energy Use (10^{12} Btu)
2063	Beet Sugar	92.7
2046	Wet Corn Milling	83.1
2011	Meat Packing Plants	64.8
2082	Malt Beverages	46.8
2075	Soybean Oil Mills	46.7
2033	Canned Fruits and Vegetables	45.2
2051	Bread, Cake and Related Products	40.6
2026	Fluid Milk	39.0
2062	Cane Sugar	33.7
2037	Frozen Fruits and Vegetables	30.1
--	Others	414.8
20	Food and Kindred Products	937.5

Energy efficiency in the food industry seems to be generally improving. Oak Ridge Associated Universities (1980) showed that the ratios of 1000 Btu per dollar value of shipments declined between 1972 and 1976 for almost all four-digit SIC categories. One possible cause for this decline is that the number of food preparation establishments has been declining in almost every sector of the food industry. The elimination of smaller, less efficient plants has resulted in a greater fraction of the total production volume from the larger, more efficient plants.

Despite the improvements in energy efficiency by the food industry, further opportunities exist for energy conservation. In 1974, about 20% of the energy consumed in the food industry was accounted for by boiler losses and other losses (Oak Ridge Associated Universities 1980). Heat recovery techniques and leak plugging could eliminate part of this loss. Other energy-intensive processes, such as heating and cooling processes, dehydration, separation processes, blanching, drying, sterilization, and fluid waste recovery, offer potential for energy conservation through efficiency improvements. Because increased efficiency in these processes largely depends on

TABLE 5.18. Energy Use by Fuel Type by Three-Digit SIC Categories in the Food Industry (SIC 20), 1976 (Lovins 1977)

SIC	Industry	Total (10^{12} Btu)	Distillate Oil (10^{12} Btu)	Residual Oil (10^{12} Btu)	Coal (10^{12} Btu)	Coke (10^{12} Btu)	Natural Gas (10^{12} Btu)	Purchased Fuels (10^{12} Btu)	Elec-tricity (10^{12} Btu)
201	Meat Products	103.3	7.6	D[(a)]	D	D	14.5	73.2	26.4
202	Dairy Products	92.5	6.9	10.0	D	--	40.2	74.3	18.2
203	Canned & Preserved Fruits & Vegetables	124.8	11.1	D	D	--	61.9	107.2	17.6
204	Grain Mill Products	139.9	D	D	D	D	64.7	120.9	19.0
205	Bakery Products	51.4	2.3	3.1	D	--	28.8	42.2	9.2
206	Sugar Products	158.3	9.0	D	D	D	D	151.3	7.2
207	Fats & Oils	105.2	D	D	D	--	56.7	94.3	11.9
208	Beverages	101.2	10.7	D	D	D	47.2	85.3	15.4
209	Misc. Products	51.3	D	D	D	--	16.6	40.3	10.0

(a) D = Withheld to avoid disclosing information for individual companies.

technological advances, these areas provide focal points for applied R&D. Too many research possibilities exist to be covered thoroughly in this brief overview. Much more detailed reviews of energy conservation in the food industry can be found in DOE 1976; Casper 1977; Johns-Manville Corp. 1976; King 1977; Rao, Katz and Goel 1978; Singh 1977; and DOE 1977. Table 5.19 and the following discussions highlight some of the major energy conservation opportunities in the food industry. Many of these are presently being addressed, at least in part, by the research efforts of DOE's Agriculture and Food Processes Branch of the Office of Industrial Programs.

Because a large percentage of the fossil fuels used in the food industry is used to provide low- and medium-temperature process heat, opportunities exist for alternative fuels use. In particular, solar thermal and low-Btu gas production from wastes are well-suited to the food industry. Battelle-Columbus Laboratories and Pacific Northwest Laboratory (1977) have made a survey of solar thermal applications. Other technological innovations in the food processing industry include low-energy concentration of fluid foods and processing effluents (perhaps using membranes instead of heat), low-energy canning methods, heat recovery from processing plants (development of high-temperature hyperfiltration is needed to remove contaminants from waste streams that make direct reuse unsafe), and advanced food sterilization/preservation techniques to eliminate some of the refrigeration requirements.

As shown in Table 5.19, some of these general industry concepts, such as heat recovery and sterilization, are also the major conservation opportunities in the specific food processing categories. For instance, in the milk and dairy products category (SIC 202) natural gas and electricity are the primary energy forms and are used to provide steam/direct heat and refrigeration. Boiler losses account for a significant fraction of the energy use in the dairy industry, but improved heat recovery systems could reduce these losses. Advanced sterilization/preservation techniques (particularly for milk) could reduce the required amounts of refrigeration in the industry. Waste heat recovery and microwave applications could be applied to the meat products category (SIC 201) to reduce the heating requirements of a meat processing plant. Hot deboning, use of outside air for refrigeration in northern plants,

TABLE 5.19. Energy Conservation Opportunities in the Food Industry

Dairy and Milk Processing	
	Alternative Processes (jet cooking...)
	Milk Sterilization
	Waste Heat Recovery
Meat Processing	
	Waste Heat Recovery
	Microwave Applications
	Hot Deboning
	Use of Outside Air for Refrigeration in Northern Plants
	Alternate Chilling Methods
Sugar Processing	
	Increased Evaporation Efficiency
	Reduced Water Requirements
	Alternate Concentration Processes (membranes)
Fruits and Vegetables	
	Heat Recovery (gases and water)
	Methane Production from Wastes
	Sterilization
General Food Industry	
	Low-Energy Concentration of Fluids Foods and Processing Effluents
	Low-Energy Canning Methods
	Heat Recovery from Processing Plants (high temp. hyperfiltration)
	Food Sterilization/Preservation Techniques

and alternate chilling methods are research areas that could reduce electricity consumption in meat refrigeration. Both the cane sugar (SIC 2062) and the beet sugar (SIC 2063) industries involve considerable evaporation and concentration of solutions through heating. Alternative methods of evaporation and concentration, such as less water-intensive processing techniques and use of membranes, could reduce this energy consumption. In the canned and preserved fruits and vegetables industry (SIC 203), the majority of energy is used to produce steam for processing fruits and vegetables. Increased heat recovery from both the gas and fluid waste streams could improve the efficiency of this process. Organic wastes could be converted to energy through biochemical or thermochemical means or through direct combustion. Sterilization methods could supplant some refrigeration requirements.

Energy use in the food industry is not concentrated in any single category. In fact, no four-digit SIC category accounts for as much as 10% of the industry's total energy consumption (Oak Ridge Associated Universities 1980). This fact indicates that applied research on energy conservation technologies cannot be targeted at a few specific food processing industries to achieve large energy savings. However, fuel use for low- to medium-temperature process heat and electricity consumption for refrigeration are generic to many categories. Thus, research to improve the efficiency of these energy uses would find broad application in the food industry. Technologies where research could be applied to reduce the energy required in process heating include solar heating systems, organic waste energy systems, waste heat recovery techniques, and low-energy water removal techniques (e.g. methods using membranes). Technologies that could reduce refrigeration energy use include chilling systems using outside air in northern climates, chillers using waste heat, and advanced sterilization/preservation techniques to eliminate the need for some refrigeration.

5.1.6 Textile Mill Products

The textile industry (SIC 22) converts natural and synthetic fibers to fabrics. Other industries further process the fabrics into clothing, upholstery, sheeting, draperies, carpets, thread, rope, and other products. In 1976, the U.S. had 7,313 textile plants, located primarily in the Carolinas, Georgia, New York, New Jersey, and Pennsylvania (Oak Ridge Associated Universities 1980). While these textile plants themselves tend to be relatively old, the equipment stock in the plants is relatively young when compared with that of other industries (Govani and Linonis 1978). Despite the newness of the equipment stock, substantial energy savings are possible in textile plants via use of appropriate retrofits or alternative processes. Some of these conservation measures offer areas in which research could promote energy conservation.

To understand how the textile industry could save energy and where R&D is needed, energy use in the industry should be examined. For convenience, processes in the textile industry can be classified as either wet or dry. Yarn formation, weaving, and knitting are dry processes; wet processes include sizing, desizing, washing, dyeing, scouring, mercerizing, bleaching, and various types of finishing processes (Arthur D. Little, Inc. 1976a). Table 5.20 breaks textiles manufacturing into nine major processes and shows the amounts and types of energy that are used in each process. Table 5.21 shows the percentages of each type of fuel used in the industry. The 329 x 10^{12} Btus of energy used in the textile industry in 1976 made it the tenth most energy-consumptive industry. That energy consumption represents about 2.6% of the total energy used by all manufacturing industries (SIC 20-39) in the U.S. (Oak

TABLE 5.20. Energy Consumption by Process in the Textile Industry (SIC 22), 1976[a]

Process	Fuel Types[b]	Total Energy Consumption (10^{12} Btu)
Spinning	Electricity	13.6
Texturizing	Electricity, Fuel Oil	7.6
Weaving	Fuel Oil, Electricity	9.8
Knitting	Electricity, Fuel Oil	3.2
Greige Mills (woven)	Electricity, Steam	19.3
Finishing (woven)	Steam, Natural Gas, Electricity	54.0
Finishing (knit)	Fuel Oil, Natural Gas	67.8
Yarn Dyeing	Natural Gas, Coal, Oil, Electricity	45.7
Floor Coverings	Natural Gas, Steam, Electricity	38.8
Other (Space Heating, Air Conditioning, Lighting, Intra-mill Transporation, etc.)	Electricity, Fuel Oil, Natural Gas, Propane	68.8
Total	All Fuel Types	328.6

(a) Adapted from Oak Ridge Associated Universities (1980).
(b) Fuel types are listed in descending order according to magnitude of consumption in each process.

TABLE 5.21. Relative Consumption by Fuel Type of Energy in the Textile Industry (SIC 22), 1978[a]

Energy Source	Percentage of Total Energy
Natural Gas	24.02
Propane and LPG	0.96
Distillate Fuel Oil (including diesel and kerosene)	3.96
Residual and Crude Oil	23.13
Gasoline	0.49
Coal, bituminous	13.45
Coal, anthracite	0.32
Electricity	33.05
Other	0.62

(a) Adapted from Oak Ridge Associated Universities (1980).

Ridge Associated Universities 1980). The Oak Ridge Industrial Energy Use Data Book (1980) contains a more detailed summary of energy use in the textile industry.

In general, the mechanical dry processes use electricity, whereas the wet processes, which involve several heating processes, tend to use fossil fuels. Because of the substantial amount of energy consumed in these heating processes, the following are likely areas for conservation effort that would involve R&D: 1) improved heat transfer techniques, 2) effective ways to reclaim and use waste heat, 3) process equipment that requires less water that needs to be heated and evaporated, and 4) methods to facilitate the use of waste products as fuels (Oak Ridge Associated Universities 1980).

Several studies have examined the conservation potential of the textile industry, particularly in the wet process segment. A. D. Little (1976a), Cook et al. (1978), Cooper (1978), and Streb (1977) provide much more detailed examinations of energy conservation in the textile industry than is presented here. Those studies estimate potential savings to range from 31% (Cook et al. 1978) to 57% (Arthur D. Little, Inc. 1976a) of the total energy used by the textile industry. Table 5.22 summarizes the major technological improvements

TABLE 5.22. Energy Conservation in the Textile Industry (Cook et al. 1978)

I. Batch Dyeing Procedural Modifications

1. dybath reuse
   - analytical system for measuring concentration of dyes
   - starting of dyes at elevated temperatures (170°F)
   - materials handling procedures made compatible with current plant procedures
   - evaluation procedure to ensure quality of dyeing in recycle baths is adequate
   - coupling of dyebath reuse with wastewater treatment systems (hyperfiltration, ozone, carbon adsorption) to reduce overall cost.

II. Predyer and Dryer Modifications

1. subatmospheric pressure drying
2. can drying using hot water instead of steam
3. machnozzle drying

III. Preparation Process Modifications

1. more efficient washing process
2. more efficient drying process
3. more efficient chemical removal of impurities
4. combination of processes (singeing, desizing, scouring, bleaching, mercerization) to eliminate energy-intensive interprocess washings and dryings

IV. Atmospheric Dye Beck Modifications

1. improved sparge control and efficiency
2. reduced housing radiative and convective losses

V. Sensors and Systems Controls

1. segregation of variable temperature waste streams for improved heat recovery
   - instruments to measure steams under harsh conditions (temperature and mass flow rate)
   - control technologies

needed to achieve this level of increase in energy efficiency. The technologies fall into five major topics: dyebath re-use, predryer and dryer modifications, preparation process modifications, atmospheric dye beck modifications, and sensors and systems controls. The items listed under each of these major topics are areas in which applied R&D could promote energy conservation. Specific research suggestions, as well as other energy conservation areas that are less dependent on research, are presented in Cook et al. (1978).

A great deal of energy conservation and energy efficiency could be achieved in the textile industry through improved engineering design, use of existing energy-conservation technologies, and application of various types of research. Specifically, because heating is predominant in the dyeing, washing and drying processes, heat transfer research could significantly impact on the industry. High-efficiency, low-cost heat exchangers and heat pipes would find broad application in improving the energy efficiency of these processes. Also, research into advanced filtration techniques could facilitate the practicality of dyebath reuse, which avoids discharging the heated bath to the sewer after each dyeing cycle. The discharged bath contains approximately half of the total energy used in conventional atmospheric dye becks. And finally, research into improved sensors and systems controls has several applications in the textile industry. Sensors are needed to accurately monitor the shade of the dyed material to avoid costly and energy consumptive reworking and redying. Sensors and controls to measure and control fluid and gas stream flows are needed in the design of efficient systems to segregate wastewater for reuse and heat recovery. Sensors are also needed to measure the moisture content of moving fabric to avoid overdrying. These areas provide a focus for applied R&D to have an important role in improving the energy efficiency of the textile industry.

5.2 IDENTIFICATION OF GENERIC INDUSTRIAL ENERGY CONSERVATION TECHNOLOGIES

To produce a general list of generic industrial energy conservation technologies, the ideas from the previous industry-specific discussions that have potential multi-industry applications were compiled. Ideas collected from a formal literature review were also added (Hopp et al. 1981) and both are presented in Table 5.23. The technologies listed are intentionally defined at a fairly general level to focus the analysis on the research opportunities for bringing the technologies to a stage in which they can be integrated into an industrial installation's engineering design. The technology and engineering development that is needed to use the technology in specific industrial applications is probably best left to industry and is therefore not considered here.

5.3 SCREENING OF GENERIC INDUSTRIAL CONSERVATION TECHNOLOGIES

As dictated by the methodology outlined in Figure 2.1, the generic industry technologies in Table 5.23 were screened according to two criteria:

TABLE 5.23. Generic Industrial Energy Conservation Technologies

Heat Exchangers
Heat Pumps
Cogeneration Technologies
Systems Controls and Sensors
Scrap Recycle
Insulating Materials
Separation (Distillation) Processes
Freeze Crystalization
Catalysts
Drying Technologies
High-Efficiency Electric Motors
High-Efficiency Air Motors
High-Efficiency Pumps
Integrated Industry Concepts
High-Efficiency, High-Temperature Burners
Alternate Fuels Combustion/Conversion
Improved Refrigeration/Cryogenics
Genetic Engineering Technology
Tribology (Materials, Lubricants)
Direct Forming Processes
Thermal Energy Storage
Electrical Energy Storage

1) Does the technology offer significant energy conservation potential? and 2) Can applied research play an important role in realizing the potential energy savings? By singling out those technologies that can be justifiably argued to meet these criteria, the information development efforts were focused on areas in which research offers the largest potential energy savings. A brief overview of the screening of the technologies in the order they appear in Table 5.23 is presented below.

Heat exchangers can be applied to the recovery of the tremendous amount of thermal energy lost as waste heat in industry. Each year, an estimated 2.0 quads are wasted at temperatures above $1000^{o}F$ (DOE 1978e). An additional 1.5 to 2.0 quads are lost in low-temperature process streams. In all, approximately 10 quads per year are lost in industrial process waste gases (Intertechnology Corp. 1977). The potential for energy conservation through recuperation of this waste heat appears to be extremely high. In addition, although heat exchanger technology is an established science, major problems such as fouling remain poorly understood. Research efforts could, therefore, play an important role in the ultimate use of this technology. A more detailed discussion of heat exchanger technology is presented in Section 5.4.1.

Heat pumps are another technology that could be used to recover industrial waste heat. These devices could upgrade intermediate- and low-temperature waste heat for recycling back into the process. Although heat pumps have recently become widely used, their applications have been primarily in low-temperature, low ΔT processes. Research and development could lead to heat pumps more suited for recovering portions of the vast amount of industrial waste heat. Heat pumps, as applied to industry, are examined in additional detail in Section 5.4.2.

Cogeneration involves the simultaneous generation of electricity and useful thermal energy. Cogeneration could save an estimated 2.0 to 3.0 quads annually by the year 2000 (DOE 1980e) and is technically feasible with present technology. However, technological improvements, such as increased reliability and fuel capability, could improve the prospects for market penetration of the technology. Cogeneration technologies are discussed further in Section 5.4.3.

Systems controls and sensors have played a large part in improving industrial energy efficiencies in recent years. Increasing industrial system complexity will provide even more fruitful applications for control technologies in the future. One study estimated that research into systems controls and sensors could ultimately save 0.8 to 8.0 quads per year (Rabbins et al. 1980). Systems controls and sensors are examined in greater detail in Section 5.4.4.

Recycling scrap materials is generally much less energy-intensive than producing new materials from ores. For example, as pointed out in Section 5.1.2.2, recycled aluminum requires only 5 to 10% of the energy needed for production of primary aluminum (Boercker 1978). Recycling of other metals, plastics, and municipal solid waste also offers energy conservation potential. Research into purification, separation, and processing could increase the potential for economic scrap recycle. The various options for scrap recycle are discussed in Section 5.4.5.

Insulation can be applied to most industrial heating processes to control unwanted heat rejection. Donnelly et al. (1976) estimates that increased insulation in industry could save about 1.5 quads per year using existing technology. Because of the magnitude of potential energy savings, even small percentage improvements in the efficacy or penetration of insulating materials could therefore have a significant impact on total energy savings. Research opportunities for improving the viability of industrial insulation are discussed in Section 5.4.6.

Distillation, the most common heat consumptive separation process, accounts for over 2 quads or nearly 3% of the nation's energy use (DOE 1980b). One option for reducing this sizeable energy use is to replace distillation processes with a physical separation process, using membranes, for example. Energy conserving alternatives to conventional distillation processes are discussed in Section 5.4.7.

Freeze crystalization is a specific separation technology that offers potential applications in concentrating foods, removing water from pulp mill black liquor, and desalinating water. The conservation potential of freeze crystalization in pulp production alone has been estimated to be 0.1 quad per year (Concentration Specialists 1979). Applications and research opportunities for freeze crystalization are discussed in Section 5.4.8.

Catalysts are widely used in industrial chemical processes. Improvements of a factor of three and higher in the total energy efficiency of chemical processes have been documented (Reikert 1974). However, present knowledge concerning catalysts is largely empirical. Additional research into the catalysis process could result in improved catalysts for use in industrial processes. Additional discussion on catalysts appears in Section 5.4.9.

Drying processes account for approximately 5% of the energy used in the industrial sector (DOE 1980e). Many alternative drying technologies, such as microwave, reverse osmosis, radiation, pressing, and pneumatic methods, have been proposed to reduce drying energy consumption. The broad range of potential research areas in drying technologies is examined in Section 5.4.10.

Recent DOE reports state that the conservation potential for electric motors in 1977 would be approximately 0.1 quad if the entire electric motor population were replaced with energy-efficient models (DOE 1978c; Argonne National Laboratory and Arthur D. Little, Inc. 1980). DOE (1978e) also states that electric motor design is a mature technology. Energy-efficient models are currently available at a slightly higher cost than conventional electric motors. Research to develop an even more efficient motor, therefore, is not considered cost effective. Electric motors are not further considered in this study as targets for energy conservation research. However, control of the system, of which the electric motor is a part, could improve energy efficiency. This option will be dealt with in Section 5.4.4 on Systems Controls and Sensors.

The approximately 3 million air motors in the U.S. consume about 0.1 quad of energy per year. Most of these motors are air vane motors, whose efficiency is roughly 0.5. According to Robert E. Barrows, Manager of Starter Development at Ingersoll-Rand Company in Roanoke, Virginia, turbine air motors offer the potential of a 50% increase in efficiency over air vane motors. If the efficiency of all air motors could be increased to 75% by switching to turbine air motors, a total energy savings of 0.03 quads would result. The technology of turbine air motors currently uses exotic materials and very close tolerances developed in the aircraft industry. Applied R&D would be needed to develop practical turbine air motors for industrial applications and the industrial environment, although some turbine air motors, which have been scaled down from designs used in the aircraft industry, are already on the market for specific industrial applications (Tech Development, Inc. 1979). Unless promising research areas that will not be addressed by the private sector are identified, the federal government should let manufacturers develop this technology. Turbine air motors are therefore not discussed further in this study.

Pumps are widely used in most sectors of industry, but only in agriculture can they become economically important. In agriculture pumps consume 13% of the sector's energy or 0.26 quads per year (Oak Ridge Associated Universities 1980). Pump technology improvements could result from research in impeller design or through use of higher efficiency motors. However, the majority of the conservation potential for pumping systems lies in improving pump selection, sizing, and control (Argonne National Laboratory and Arthur D. Little, Inc. 1980). These areas would appear to require engineering development rather than applied research. Because of the smaller energy flow addressed by pumps than by other generic industrial energy conservation technologies and their lack of need for applied research, they are not considered further in this study.

Integrated industry concepts involve use of waste heat from one industry or process as a heat source in another industry or process. Such cascading of energy use could improve the overall efficiency of industrial energy use. An analysis of the waste heat flows in industry, with consideration of the potential for energy cascading, is needed. The technology required to implement integrated industry strategies would mainly be heat exchangers and heat pumps, technologies that are being considered separately in Sections 5.4.1 and 5.4.2, respectively. Since no unique research requirements are apparent for integrated industry concepts, this area is not considered further.

The prevalence of high-temperature processes in industry makes high-efficiency, high-temperature burners a promising potential energy conservation technology. The steel, glass, and ceramic industries possess high-temperature processes with exhaust gas temperatures of 2000°F. Old burners could only use 1000°F to 1200°F preheated air. However, the most recently developed high-temperature burner, Hague's Transjet burner, can accept 1500°F air and according to their literature, is capable of reaching 1800^{O}F (Young, Campbell and Worstell 1981). Because of this development, the potential for additional applied research would appear to be small. High efficiency burners are therefore not considered further in this study.

Use of alternative fuels to oil and natural gas, such as coal, synfuels, and slurries, could supply large amounts of industrial process heat, which accounts for over 16 quads per year (Lovins 1977). However, problems with lack of knowledge about fuel characteristics, fuel/engine compatibility, and emissions may hinder their adoption by industry. Because of alternative fuels' potentially massive impact on industrial energy use, this area is discussed further in Section 5.4.11.

Refrigeration and cryogenics have received fairly little attention in the energy conservation literature. Because of the paucity of data and because the applications would seem to be primarily confined to the food processing industry, this technology is not addressed further in this report.

Genetic engineering technology could be applied to developing organisms for converting biomass to fuel or chemical feedstocks. Because of the broad potential applications and the newness of this technology, a further examination is presented in Section 5.4.12.

Tribology is the science of friction, wear, and lubrication. Both friction and the wear of parts result in substantial energy losses in virtually all industries. One source estimated that industry could save 1.3% or about 0.4 quad of energy through reduced friction and wear (Jost 1975). Because of the wide application and large potential savings through tribology, this area is considered in more depth in Section 5.4.13.

Direct forming processes, such as powder metallurgy, spray forming, injection molding, and advanced forging and rolling processes, offer an option to decrease both energy and materials wastage. As pointed out in Section 5.1.2.1, the direct forming process of powder metallurgy is a potential energy conservation option for the steel industry. However, despite that potential, they are difficult to evaluate as a generic technology. The energy conservation potential and research opportunities are intimately tied to the specific application. Thus, a comprehensive analysis that compiles and compares the numerous applications of direct forming processes would be useful to evaluate this technology. Such an analysis is beyond the scope of this study, however; therefore, direct forming processes are not discussed further.

Thermal and electrical storage in industry would integrate well into heat recovery, solar, and possibly cogeneration systems by allowing energy to be stored for future use. Presently, cost is the major impediment. Therefore, research should be directed toward reducing the cost of industrial applications of storage technologies. Because DOE already has an ongoing storage program that is involved in assessing the research opportunities in this area, industrial energy storage technologies are not covered in this report.

5.4 SELECTED INDUSTRIAL ENERGY CONSERVATION RESEARCH OPPORTUNITIES

Sections 5.4.1 through 5.4.12 present capsule summaries of the information developed for the technologies selected for further analysis in the previous section. These discussions examine the conservation potential, possible research opportunities, and other issues that affect each technology's potential role for applied R&D. The overall intent of these summaries is to provide sufficient information for a research program manager to decide which areas are sufficiently attractive to be considered further for possible funding.

5.4.1 Heat Exchangers

As mentioned in Section 5.3, waste streams have been estimated at 10 quads/yr, which translates to 13% of the energy consumed in the U.S. The potential for waste heat recovery in 1985 has been estimated as 5-7 quads/yr (DOE 1978e). The maximum potential for conservation through heat exchanger use has been estimated as 15.4 quads, or virtually all of the waste heat generated by industry in the year 2000 (Adolfson 1979). The true conservation potential through heat exchanger development is a more complex question because advances in this technology may increase the attractiveness of other technologies such as heat pumps and cogeneration. However, without further analysis the potential energy savings through greater development and use of heat exchangers are clearly very substantial.

Although heat exchangers are often viewed as a mature technology, a pressing need to resolve problems through applied R&D still exists. Research is needed to address both persistent problems and innovative options to conventional heat exchangers. Through greater understanding of the characteristics of the problems and concepts, important improvements can be achieved in reliability, performance, and cost. Research topics include the investigation of fouling, corrosion, vibration, and heat transfer enhancement. Continued development is needed of ceramic heat exchangers, fluidized bed heat exchangers, plastic heat exchangers, heat pipes, direct contact heat exchangers, and small particle heat exchangers. Brief overviews of these areas are presented below.

Fouling

Industry and academia consensus indicates that research into fouling warrants particularly strong emphasis. Fouling problems affect virtually all end-use sectors because of the particulates and impurities present in many waste streams. Problems exist in processes ranging from low-temperature food processing waste streams to high-temperature exhaust streams of low-quality fuels.

To date little research has been performed in this area. Hence, an understanding of the mechanisms of fouling and experimental data bases are generally poorly developed.

Corrosion

Contrary to the little attention fouling problems have received, corrosion issues relating to heat exchangers have seen extensive study. The many variables involved in corrosion have made this topic difficult to deal with. Traditional solutions in high-temperature environments have been to use resistant alloys, which have also increased the heat exchangers' cost. Past efforts have also been directed at specific problems operating under specific conditions.

Information regarding general corrosion rates and processes requires additional research that will become increasingly important as the industry moves to poorer quality fuels and as it becomes more desirable to recover heat from low-temperature streams.

Flow-Induced Vibration

Flow-induced vibration is a significant cause of decreased heat exchanger reliability and life. Prediction of the onset and degree of flow-induced vibration has been very difficult and continued work appears to be needed to more thoroughly understand the causes of this phenomenon.

Enhanced Surfaces

Enhancing the gas-side heat-transfer coefficient on heat exchangers is a continuing challenge in heat exchanger design. In a gas-liquid heat exchanger the gas-side heat-transfer coefficient is normally several times smaller than the liquid side; hence, the controlling or dominant resistance to heat transfer is on the gas side. Improvements in this area would reduce the required size of a heat exchanger and, consequently, reduce the cost.

Attempts to increase heat transfer have often been frustrated by increasing pumping power requirements. One way to circumvent these requirements is to induce surface disturbances between 0.3 to 1.0% to increase the heat-transfer coefficient without significantly affecting the pumping requirements (Klaschka 1979).

High-Temperature Heat Exchangers

High-temperature ceramic and metallic heat exchangers have received extensive attention in recent years because high-temperature streams have a high degree of available work and may be used more effectively. Above 2000°F, the ceramic exchanger is the necessary choice of heat exchanger material (Argonne National Laboratory 1979). Besides their high temperature capability, ceramic heat exchangers can resist corrosion in hostile environments and are potentially less costly than metallic heat exchangers.

Ceramic exchangers are anticipated to be critically important to the effective use of low-grade fuels, such as coal, peat, and residual oil, in externally fired engines, where temperatures and corrosive environments would quickly degrade a metallic exchanger. Other applications include furnace waste heat recuperators, vehicle gas turbine recuperators, fluidized bed exchangers, Stirling engine exchangers, MHD air preheaters, and fusion plant exchangers.

Although many firms are involved in developing ceramic exchangers, most are supported by government funds and several problems remain before this technology will experience notable penetration. Several areas need research to resolve problems (McDonald 1980):

- design techniques for brittle materials
- fabrication costs
- fabrication limits
- permeability
- service life
- high-pressure designs
- repair techniques.

The tremendous potential for use in high-temperature and corrosive processes and the diverse range of applications indicate that this technology receive high priority for further research.

Fluidized Bed Heat Exchangers

Fluidized bed heat exchangers possess two significant advantages over conventional heat exchangers: a very large gas-side heat transfer coefficient and improved fouling resistance. The increase in heat transfer coefficient is typically an order of magnitude, although a 50-fold improvement was observed with a dense bed of small particles (50 micrometers) (Aerojet 1980).

Experience with fluidized bed technology has been gained through early work with fluidized bed gasifiers, which have been used in the chemicals and petroleum industries since the 1930s. Experience has also been accumulated through recent work on fluidized bed combustion systems. However, gasifier development has been directed at pressurized systems and the heat exchanger typically operates at atmospheric pressure. The gasifier also does not have a heat exchanger surface immersed in the bed. In the case of the combustion system, heat is generated in the bed at high temperatures, $1500^{o}F$ to $1600^{o}F$. The heat exchanger typically operates at intermediate temperatures, $300^{o}F$ to $700^{o}F$, without in-bed combustion.

A major problem with fluidized-bed heat exchangers has been the difficulty in accurately measuring the heat-transfer coefficient. Order of magnitude differences in reported results are not uncommon. These differences are due to both the complex mechanisms of the heat exchange process and wide range of researchers generalizing results to a wider range than is appropriate.

The following include several of the design uncertainties of fluidized bed heat exchangers (Argonne National Laboratory 1979):

- overall heat transfer coefficient
- fluidization characteristics or quality
- bed expansion characteristics
- attrition rates of particulate solid media in the bed
- system control
- system life.

Plastic Heat Exchangers

Plastic heat exchangers have the potential for significant application in low-temperature processes. These heat exchangers would be especially valuable in streams containing potentially corrosive contaminants. For example, SO_2 is emitted as a combustion product from certain internal combustion engines, fossil fuel fired boilers, and gas turbines. SO_2 reacts with oxygen to form SO_3 and when the temperature drops below its dew point temperature, it condenses to form sulfuric acid, which normally attacks metallic surfaces. In normal operation the temperature is therefore kept above the dew point, resulting in a loss of recoverable energy. The corrosion resistance of plastic heat exchangers enables operation at temperatures below the dew point with a resultant increase in the recovery of sensible heat and the added recovery of latent heat.

In addition to corrosion resistance, plastic heat exchangers have several advantages:

- low cost
- chemical inertness
- flexibility
- toughness
- unique surface properties that can promote boiling, condensation, and resistance to fouling.

Composite materials could be used in heat exchangers. Composites, which may be formed through the addition of metals, fibers, or plasticizers, strengthen the mechanical properties and increase the thermal conductivity and heat distortion temperatures.

Dupont has been marketing Teflon™ tubed heat exchangers since 1965; however, little work in other options seems to have been performed.

Examples of R&D opportunities include the following performance studies (Miller et al. 1979):

- plastic or composite plastic mechanical and thermal properties
- properties-enhancement techniques
- fabrication techniques.

Heat Pipes

Heat pipes have received increasing attention because of their high efficiency and their ability to ensure no cross-contamination between the fluid streams. Additionally, heat pipes circulate working fluid without any moving parts. Recent applications of heat pipes include gas-to-gas heat exchange from food and textile dryers.

A primary deficiency in current heat pipes is their inability to operate at temperatures above 300°C with an acceptable working fluid. Current organic fluids capable of being used at temperatures above 300°C are unacceptable in terms of other characteristics such as flammability and toxicity. A working fluid that is thermally stable above 300°C, nontoxic, nonflammable, and noncorrosive is thus needed. Characterization of current fluids near their critical point is also needed. The need for additional research into organic working fluids for heat pipes is very similar to the need for organic working fluids in heat pumps and in bottoming cycles. Research also needs to address the challenge of increasing the gas-side heat-transfer coefficient. This problem was discussed as a separate topic in the section on enhanced surfaces.

Direct Contact Heat Exchangers

Direct contact heat exchange between two immiscible fluids offers the potential for efficient heat exchange. Current applications of the technology have been limited primarily to heat recovery from geothermal brine, although industrial use is being investigated. Attractive industrial applications include exhaust gas streams laden with particulates that induce fouling and corrosion in conventional heat exchangers. Several such waste streams in the

175°F to 750°F temperature range have been identified by Semler et al. (1981) at EG&G, Inc. These streams include exhaust stack gases from boilers and diesel engines. Other possibilities include waste heat from drying, heating, heat treating, baking, curing, and evaporating (Semler et al. 1981).

Advantages of direct contact heat exchange include design simplicity, a single column needed for mixing the fluids, and the resultant lower cost. A cost savings of 20 to 1 over a conventional heat exchanger has been reported (Parkinson 1980). As previously mentioned, direct contact heat exchangers can also handle fouling or corrosive waste streams, thus permitting recovery of the streams' latent heat and can provide a large surface area per unit volume for heat transfer.

Problems with direct contact heat exchangers include solubility and loss of the working fluid and backmixing, which reduces the heat transfer coefficient.

Examples of more specific research opportunities have been suggested by Semler et al. (1981):

- To facilitate recuperation from highly particulate laden streams, characterization of the contaminants in these streams is needed. The development of active and passive cleaning systems for the working fluid would significantly increase the applicability of this technology.
- High-temperature (greater than 750°F) working fluids need to be developed to enable operation in the many high-temperature waste streams. Preceding this, a comparison with recuperation via conventional heat exchangers should be performed to see if the direct contact heat exchanger will offer any advantages.
- Determination of heat transfer coefficients and research into working fluids should be performed to provide a data base.

In addition, high-temperature gas-solid arrangements need to be investigated.

Because of the technology's simplicity, resistance to fouling and corrosion, and good heat transfer characteristics, it warrants further investigation.

Small Particle Heat Exchangers

Small particle heat exchangers operate through the mode of radiant heat exchange. This technology would only apply to very high-temperature heat recovery, such as from the exhaust of steel blast furnaces. For example, submicron size carbon particles could be used to absorb the radiation emitted from a hot gas stream. Upon absorption, the carbon would oxidize to CO_2, resulting in a clean stream of very hot air.

Few applications of this technology exist now, but this concept should be considered as the industry moves toward the use of higher temperatures. Extensive research relating to heat exchangers and heat transfer phenomena exists in both the government and private sectors. Idaho Falls National Labs has absorbed the Pittsburgh Energy Technology Center (PETC) heat exchanger program, which was sponsored by DOE's Office of Fossil Fuels. The Office of Industrial Programs is sponsoring several demonstration programs, which include high-temperature ceramic and metallic heat exchangers and reradiant heat exhcnagers. In the private and academic sectors a wide range of research is under way from basic studies of heat transfer phenomena to nearer-term marketing efforts. Activities range from the basic studies at the Heat Transfer Research Institute to high-temperature heat exchanger development at Hague International to low-temperature plastic heat exchanger development at Dupont.

The only nontechnical barriers to greater use of advanced heat exchangers appear to be those which any major capital investment faces; the high rate of return and short payment times required are the primary barrier. However, because heat exchangers are also integral elements of many processes, replacement would not necessarily be the addition of a technology, as is often the case with cogeneration and heat pumps. New technology inflexibility and sensitivity to misuse are other issues of concern.

As mentioned in the introduction, improvements in heat exchangers are not simply increases in effectiveness but are also directed at previously little-used flows in low- and high-temperature applications. Heat exchanger developments are also critical steps in advancing and penetrating other energy-conserving technologies, such as heat pumps and cogeneration bottoming cycles. Penetration will also occur in the increasingly corrosive exhaust streams, resulting from the shift to lower-quality fuels.

Although the added energy savings from improved heat exchangers are difficult to quantify, they can reasonably be expected to be significant. If advances were anticipated to increase use by 10 to 20%, the maximum savings by 2010 would be about 1.5 to 3.0 quads/yr.

Several programs addressing the research opportunities discussed here are under way at Idaho Falls National Lab. Work in alternate exchangers such as fluidized bed and plastic has been identified by Idaho Falls but is not being investigated because of funding limits.

From this overview the area of heat exchanger technologies is strongly recommended to continue to receive high priority for research support. Research in mitigating persistent problems such as fouling and corrosion, as well as research directed at developing new technologies such as high temperature ceramic, fluidized bed, and plastic heat exchangers are all anticipated to contribute significantly toward greater energy efficiency.

5.4.2 Industrial Heat Pumps

A heat pump's performance is typically measured in terms of a coefficient of performance (COP). The COP is the ratio of useful thermal energy delivered by the heat pump to the energy consumed by the heat pump.

Industrial processes reject large quantities of intermediate- and low-temperature waste heat at a temperature too low for economic power conversion. Industrial heat pumps can be employed to recover the energy in the waste streams, to increase the temperature, and to recycle the energy to the process. The heat pump thus upgrades energy that would otherwise be wasted and always returns more energy than it consumes.

Commercial industrial heat pumps typically recover energy from a 60^{o}F to 80^{o}F waste stream and return heated water at temperatures up to 220^{o}F to 250^{o}F. MTI, Inc. has recently developed a higher temperature heat pump that uses a 150^{o}F waste stream to return low-pressure process steam at 250^{o}F to 300^{o}F. In the 120^{o}F to 250^{o}F temperature range, the upgraded process heat can be used in applications such as food processing, grain drying, textiles, and metal cleaning. Increasing the output temperature broadens the end uses to include paper and allied products, chemicals, petroleum, stone, clay and glass, and metals.

The heat pump cycle commonly used to date has been a Rankine cycle driven by an electric motor or another Rankine cycle. The combined-cycle arrangement is referred to as a Rankine-Rankine heat pump. However, many alternative cycles and combinations exist and are being explored for various applications. Several other heat pumps are available or are being developed:

- Brayton-Rankine
- Stirling-Rankine
- Brayton-Brayton
- Stirling-Stirling
- Ericsson-Ericsson
- Absorption.

The Stirling cycle looks appealing in the generation of high-temperature steam, while the Brayton is more suitable for generating high-temperature air. The absorption cycle is the simplest mechanically with its pump being the only moving component.

The thermal energy source for heat pumps lies in the large amount of industrial process heat wasted each year. Several studies have estimated that approximately 10 quads/yr of heat is rejected by the industry (Intertechnology Corp. 1977; Burton and Chaudoir 1980). The temperature distribution is shown in Figure 5.3. If advanced heat pumps that can produce low-pressure steam at 250^{o}F are assumed to be used, an estimated 0.8 to 2.0 quads/yr can be conserved by 1985 (McDonald 1980; Drexel University 1976; Sullivan 1979). By 2000 the maximum penetration is estimated to be 2.9 quads/yr (Adolfson 1979).

Heat pumps typically derive their energy from two sources: the waste heat stream and a heat engine, electric motor, or absorption cycle. The various heat engines that may be used with heat pumps allow considerable alternate fuels flexibility. In some arrangements the waste heat stream also supplies the energy needed to drive the heat engine. Similarly, the only external energy required in the absorption cycle is the pumping power needed to circulate the fluid.

Investigating the various cycles permits comparisons of both the efficiency differences among cycles and their operating temperature ranges. For example, the Stirling cycle is theoretically more efficient than the Brayton and is best suited for high-temperature operation. The absorption cycle may

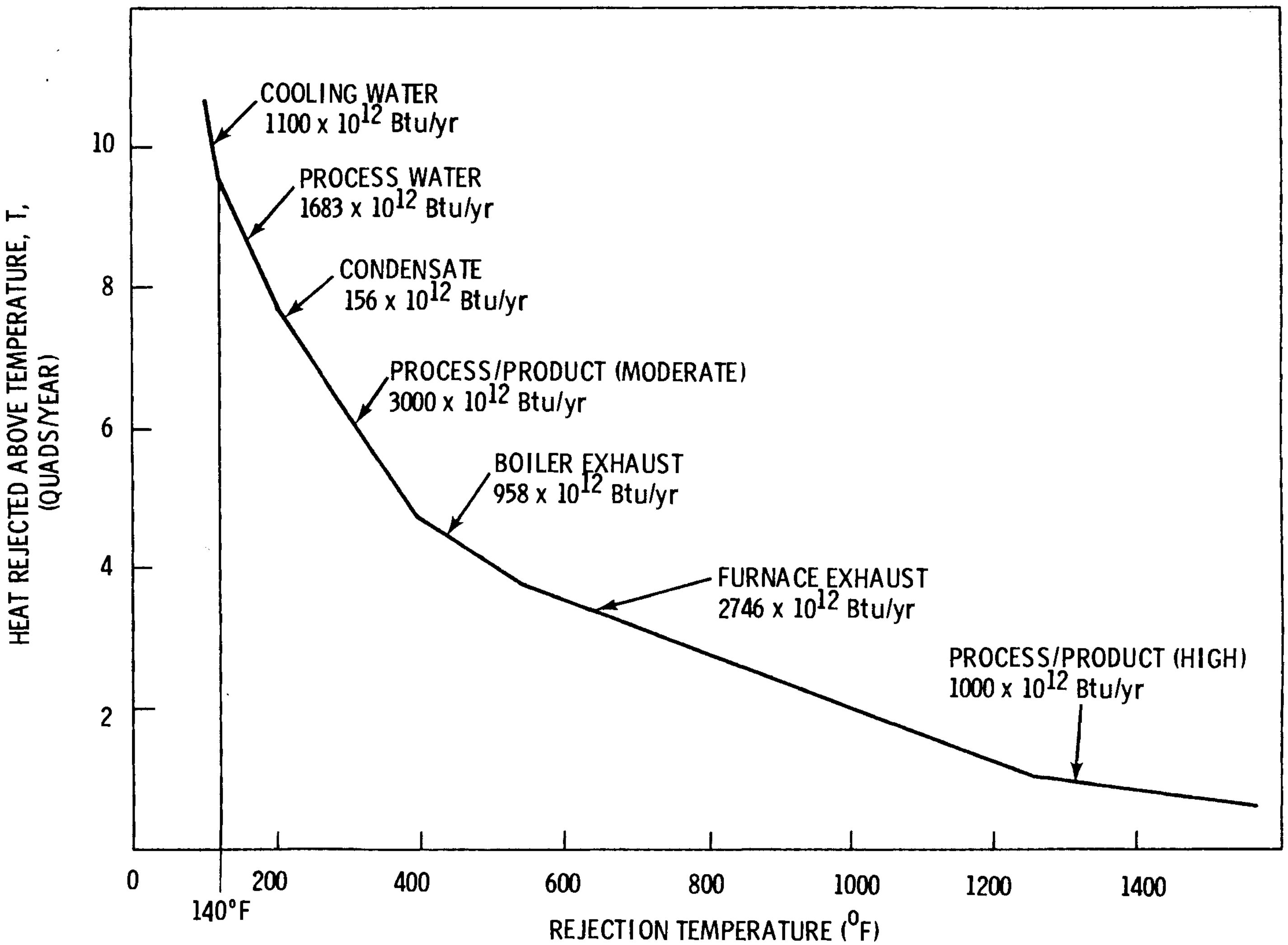

FIGURE 5.3. Temperature Distribution of Industrial Waste Heat (DOE 1978d)

compare very favorably in terms of its COP, but it also has large capital requirements. Hence, efficiency improvements alone are not the only measure of comparison.

Developing higher temperature heat pumps markedly would increase the energy conservation potential of this technology. Increasing the outlet temperature to 500°F would more than double the process heat market from the 250°F maximum currently assumed (Intertechnology Corp. 1977). Further increasing the outlet temperature to 800°F would triple the potential market. Research and development of various heat pump cycles would aid in enabling a greater breadth of applications in waste heat recovery and in needed efficiency and cost improvements.

The variety of heat pump cycles and combinations present unique research opportunities. The cycles have also received widely disparate levels of development. Rankine cycles possess the most mature and well understood elements, and most of the component development directed at efficiency improvements or cost reductions are expected to be evolutionary in the private sector. The Ericsson cycle is perhaps the least well characterized and therefore would elicit broader engine development.

Because of the many possible cycle combinations, all the options will not be treated individually. Rather, the most attractive long-term options and the most critical research opportunities will be discussed briefly below. The topics that have been identified as warranting further developments include organic working fluids, heat exchangers, Stirling cycles, absorption cycles, and Ericsson cycles.

Rankine Cycle Working Fluids

As mentioned, the components that compose steam Rankine cycle heat pumps are generally mature technologies. However, below 1000°F organic fluids become thermodynamically more attractive than steam as the working fluid. Various organic fluids such as R-12, R-22, and R-114 are commonly used in industrial heat pumps up to approximately 220°F to 250°F. At higher temperatures these fluids become thermodynamically unstable, however. Although organic fluids that are stable up to 750°F exist, these fluids possess other undesirable properties. For example, toluene is stable up to 750°F but is also highly flammable and has a very low vapor pressure.

Several studies have assessed available fluids, but little work has been done to develop a fluid with desirable characteristics. Such a fluid would have the following characteristics:

- thermally stable at high temperatures
- nonflammable
- nontoxic
- noncorrosive
- high in latent heat.

The compatibility of components that will operate with the new fluids also needs attention. Differences in viscosity and stability in operation are among the parameters that need to be characterized.

Heat Exchangers

Common to all heat pump cycles is the need for continued heat exchanger development. Heat exchangers tend to dominate the cost of the various systems through their size. The finite size of heat exchangers also creates inefficiencies by forcing the heat pump to operate between larger temperature differences than the sink and source differential. The inefficiencies and costliness in heat exchangers particularly penalize the Stirling and absorption cycles because of the large sizes typically required. Possible advances include the development of fluidized bed and low-cost plastic heat exchangers.

Stirling Cycle Heat Pumps

As a prime mover, the Stirling cycle possesses the advantage of a high theoretical efficiency (Figure 5.4). A Stirling-Rankine heat pump would be an advantageous combination of the latent heat effect in the heat pump and the high efficiency of the driver.

The Stirling-Stirling combination also possesses interesting possibilities because the heat pump is not as temperature limited by the working fluid as is the Rankine cycle. This high-temperature capability enables operation at temperatures above 400^{o}F, which could be used in the production of 150 psig process steam for the petroleum or chemicals industry. However, the Stirling engine has yet to be commercialized and current developmental engines are only able to achieve efficiencies of 20 to 22%, less than half of their theoretical efficiency.

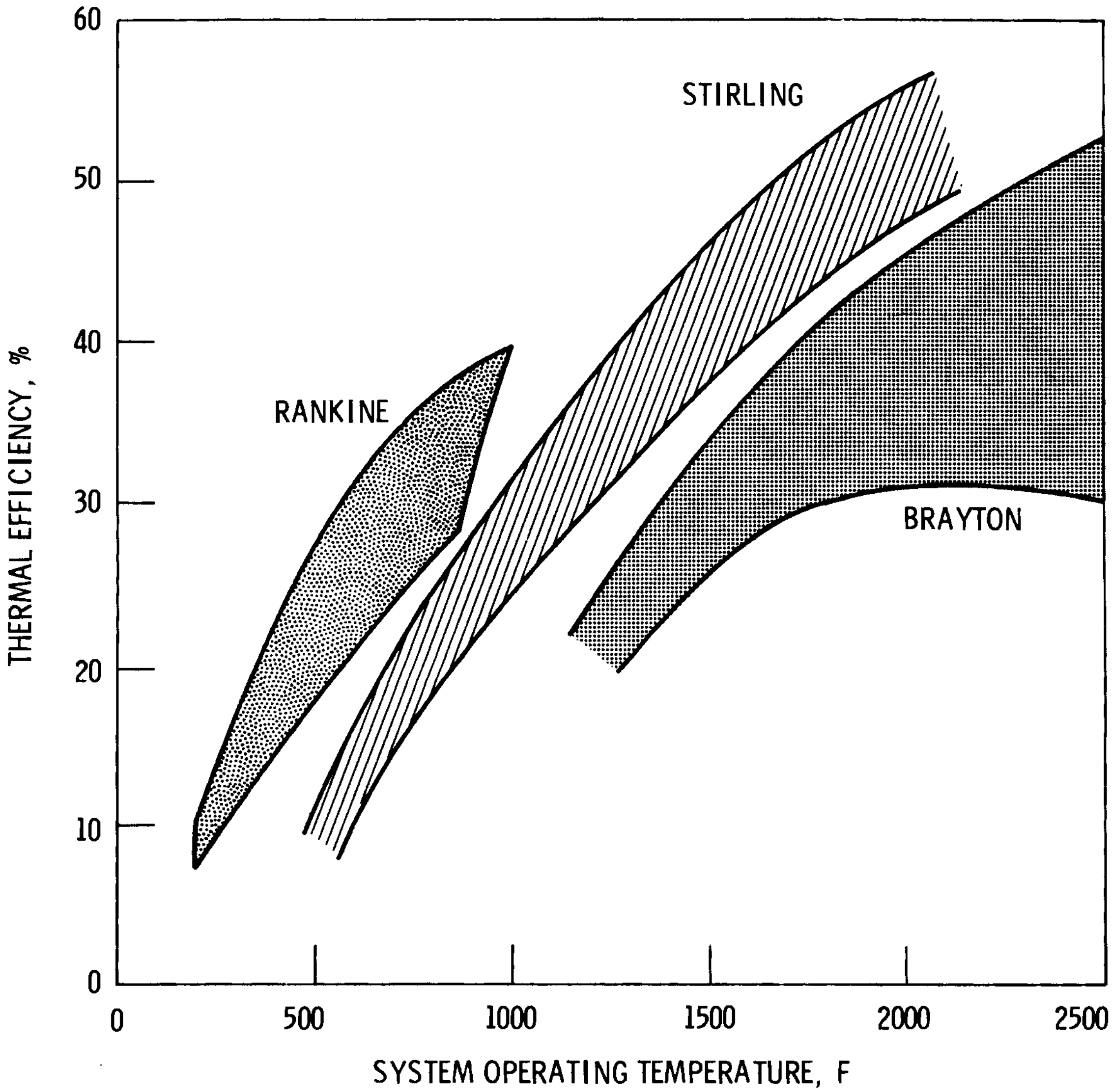

FIGURE 5.4. Temperature Efficiency Versus Operating Temperature in Prime Movers (Drexel University 1976)

Continued development is needed in several aspects of the Stirling heat pump. An important development toward increasing efficiency is more complete isothermalization. Without this, the cycle approaches adiabatic operation, which significantly diminishes its performance.

Absorption Cycle Heat Pump

The salient advantage of the absorption cycle heat pump is the minimal amount of external energy required. Although absorption cycle machinery typically involves a larger capital investment than competing cycles because of larger heat exchanger requirements, significant fuel savings can compensate for this.

Research in this area still needs to be performed to develop more efficient, multi-staged, multi-effect heat pumps. Also, high-temperature fluid pairs need to be studied and developed to enable elevated temperature operation. The properties of working fluids are currently poorly characterized at high temperatures, and materials compatibility problems (e.g., corrosion) at these temperatures are not known.

Ericsson-Ericsson Cycle Heat Pump

The Ericsson-Ericsson cycle heat pump combination offers many of the same efficiency advantages as the Stirling-Stirling cycle heat pump. The working fluid, typically helium or hydrogen, is also not as temperature limited as the Rankine working fluids. A proponent claims to have achieved 90% of the theoretical carnot COP (Benson 1978). However, the design has been directed at a residential system, and little data exist for higher temperature industrial applications.

Because of the heat pump's significant energy conservation potential in all end-use sectors, many research programs, sponsored by both the government and industry, are under way. The emphasis in the private sectors is centered around space heating and cooling.

The Office of Industrial Programs in DOE is cosponsoring several demonstration industrial heat pump projects, including a Brayton-Rankine heat pump in a solvent refining process, a Rankine cycle-steam recompression heat pump in an acetone recovery plant, and a high COP electric heat pump in a kraft paper plant. Oak Ridge National Laboratory and Battelle-Columbus Laboratories also have been involved in developing industrial absorption cycle heat pumps.

Many major private firms are involved in the research and commercialization of heat pumps. Involved with industrial heat pumps are Westinghouse, which is marketing an electric-Rankine "Templifier" heat pump, MTI, which has also developed an electric-Rankine heat pump, Carrier Corporation, and General Electric. The Institute of Gas Technology is primarily involved with residential heat pumps, although they have performed extensive work in fluid compatibility studies for absorption cycles. The Gas Research Institute is sponsoring research in several cycles, including an absorption cycle heat pump, a Stirling-Rankine heat pump, a Brayton-Rankine heat pump, and a Rankine-Rankine heat pump. However, as with the Institute of Gas Technology, most of the work has been directed at space heating and cooling. In the mid-1970s several organizations assessed the field of organic working fluids for heat pumps and bottoming cycles. Among these were Monsanto, Thermo Electron, Sunstrand, and the National Highway Safety Council.

Institutional barriers to the application of heat pumps appear to be minimal. The primary nontechnical barriers appear to be similar to those of other energy-saving technologies. Because of the minimal experience with industrial heat pumps, plants are often hesitant to employ them without an industrial demonstration. Earlier applications were also restrained because of reliability problems with heat pumps marketed in the 1960s.

Application of Rankine cycle heat pumps in low-temperature operations appears promising without a high level of government support. Development of the Stirling cycle heat pumps would certainly be slower, as would the development of the absorption cycle heat pumps. However, the major portion of unrealized energy conservation would be in higher temperature processes where current working fluids are largely unacceptable. The maximum potential lost is about 1 to 3 quads. The area of working fluids for both Rankine and absorption cycles is therefore the least explored major research need in current programs.

Heat exchanger development directed toward heat pump applications also appears minimal. Lehigh University is currently on contract with the Office of Industrial Programs to investigate fluidized bed heat exchangers for heat pumps, but this appears to be a low-level effort.

Work in Stirling and absorption cycles is under way in the organizations already mentioned.

In addition to specific technical study, two other topics have also been suggested as important to maximum heat pump penetration into industry. First, specific areas where heat pumps would be attractive should be identified in industry. Thermodynamic limitations on efficiency would eliminate certain processes, and the profile of the market potential should be assessed. Secondly, industrial process capability needs to be assessed. Deploying heat pumps in current processes alters their energy balance. Determining methods of adaptation would both enhance a practical market assessment and accelerate heat pump penetration.

5.4.3 Cogeneration Technologies

Cogeneration is the simultaneous production of electricity or mechanical energy and useful thermal energy. When the energy for producing electricity or mechanical work is extracted from a thermal stream prior to an industrial process, the technique is termed topping. Conversely, when electricity or mechanical energy is extracted from the source stream after the industrial process, the technique is known as bottoming.

Cogeneration possesses several important advantages over the separate generation of process heat and electricity. Energy is used more efficiently in terms of both the first and second laws of thermodynamics and the energy savings are often translated into dollar savings for the industrial user. Cogeneration also provides fuel flexibility to the user, generally reduces harmful effects on the environment, and can enhance power reliability.

In a "typical" process, 1 barrel of oil is used to produce 600 kWh of electricity and 2.25 barrels of oil are used to produce 8,500 lbs of process steam. Through cogeneration via a topping cycle, only 2.25 barrels of oil are required to produce both the steam and electricity (DOE 1978a).

Cogeneration is applicable to almost all industrial end use-sectors in which process heat is used, and the technology needed to employ it has long been available. At the turn of the century, cogeneration produced 58% of the power consumed in industry. However, by 1950 this percentage had reduced to 15% and by 1977 was only 4%.

After reliable utility grids were developed in the 1920s, cogeneration use began to decline. The grids provided less expensive and very reliable electricity. Other factors contributing to the decline included increasing regulation over all forms of electrical generation, utility policies discouraging onsite generation of electricity, low-energy costs representing a declining percentage of overall costs, changing corporate income tax structures, and advances in technology such as the "package boiler" (DOE 1978a).

The energy situation of the past decade has revived the industry's interest in cogeneration as a stable source of less expensive electricity. Current and developing technologies offer a plethora of options to the basic components. Prime movers tend to most strongly affect the system's efficiency. Several options for topping are possible:

- steam turbines
- gas turbines
- diesel engines
- Otto engines
- Stirling engines
- thermionic converters.

Some bottoming cycle prime mover options also are possible:

- steam Rankine engines
- organic Rankine engines
- gas turbines.

Other major components typical of topping and bottoming cycles include the combustion system (if external to the prime mover), heat exchangers, and compressors.

Several studies have been performed to estimate cogeneration's potential contribution to energy conservation. The Office of Industrial Programs and Resource Planning Associates have estimated cogeneration's energy efficiency improvements over the separate generation of steam and electricity to be 15 to 18% (Intertechnology Corp. 1977) and 15 to 23% (Resource Planning Associates 1977), respectively. Technically feasible penetration by 1985 translates to 1.1 to 1.6 quads/yr with probable penetration by 1985 being 0.1 to 0.4 quads (Intertechnology Corp. 1977; Resource Planning Associates 1977). By 2000 the Office of Industrial Programs estimates that 2.0 quads/yr could be saved with moderate penetration and 3.0 quads/yr with total penetration. The maximum theoretical energy fuel savings that could be achieved via bottoming cycles have been estimated at 1.4 quads/yr by 2000 (Adolfson 1979).

DOE's Fossil Fuels Division has recently published a Cogeneration Technology Alternatives Study, which was performed by United Technology Corporation, Westinghouse, and NASA Lewis (1980). The study investigated advanced systems that could promote the use of coal or coal-derived fuels in industrial cogeneration (NASA-Lewis 1980). The primary advancements assumed were the availability of atmospheric and pressurized fluidized bed (AFB and PFB) combustors, the development of turbine protection from the erosive and corrosive effects of PFB gases, and the ability of open-cycle gas turbines to use minimally processed coal-derived liquid fuels.

The study concluded that use of these advanced systems could increase fuel savings by 40 to 80% over savings attained with currently available cogeneration equipment (NASA-Lewis 1980). These results would increase advanced systems' projected savings in 1990 from 0.2 to 0.3 quads/yr to 0.35 to 0.45 quads/yr. These results are on the same order as projections by the Office of Industrial Programs and Resource Planning Associates, indicating energy savings of 0.1 to 0.5 quads/yr by 1985-1990 to be a consistent range.

The technology necessary for economic cogeneration is available for many plants. In the past few decades the primary barriers have been institutional. The generic components necessary for both topping and bottoming cycles, heat exchangers, turbines, combustors, and compressors are fairly mature technologies. Therefore, evolutionary efficiency improvements and cost reductions are anticipated to occur in the private sector. For example, organic fluid steam turbines are expected to improve from the current 70 to 75% efficiency range to 85% by 1990 at 25 to 50% of the size of an equivalent state-of-the-art power turbine (NASA-Lewis 1980). Similarly, boilers are expected to become smaller and less expensive through improved control and fouling technology. Condensors are also expected to decrease in size through experience gained with organic fluids.

Industry contacts revealed that alternate fuels technology was the primary area through which applied research could enhance cogeneration penetration. Coal, synfuels, and residual fuels are expected to see increasing use, and improved methods of combustion, pollution control, and energy extraction are necessary before the lower grade fuels can be used. In Resource Planning Associates' (1977) study of cogeneration they also discovered that their industrial contacts generally agreed that multifuel capability was their primary recommendation for federally funded research. They also found that improving operability and reliability was more important to their industrial contacts than improving the component efficiency. Bottoming cycle equipment will also benefit from the ability to operate with erosive gases. However, the primary need in bottoming cycles is to develop better high-temperature working fluids.

The following are examples of research in alternate fuels combustion, component compatability, component improvements, and working fluids.

Fluidized Bed Combustion

Many in industry considered fluidized beds to be a critical technology to the widespread use of coal and other low-grade fuels in industry. Besides this multifuel capability, fluidized beds offer other advantages, including effective direct capture of sulfur dioxide from coal, low NO_x emissions, unobjectionable solid wastes, and the ability to be shipped in modules.

Extensive work has been performed on both atmospheric fluidized beds that are near commercialization and pressurized fluidized beds. This work has centered around single-stage units that are limited to 1500^{o}F to 1600^{o}F for effective sulfur removal. To obtain higher temperatures, research might be performed to develop two-stage units that could be used with high-temperature heat engines such as the Stirling (NASA-Lewis 1980).

Alternate Fuels Combustion

To aid in accelerating the use of lower grade fuels, research should be conducted to optimize their combustion. To avoid redundancy with the extensive work being done with coal combustion in fluidized beds, these efforts might focus on low-grade residual oil combustion and the combustion of other noncoal derived fuels. This is a critical step toward greater cogeneration penetration.

Component Compatability

Components such as the gas turbine must be protected from the erosive and corrosive products of coal and low-grade fuel combustion. This effort is also considered extremely important.

High-Temperature Gas Turbine

A gas turbine operating with a turbine inlet temperature of 2500°F is estimated to be 10 to 15% more efficient than a state-of-the-art turbine operating with a turbine inlet of 2100°F. Research could be directed at either improved materials or improved cooling methods. One such cooling method is transpiration cooling in which the cooling air passes through the pores of the air foil and into the boundary layer to insulate the blade surface from the hot gas.

High-Temperature Air Preheaters

Combustion air, often available at 1500°F to 2000°F and above, is largely used because of the large heat exchanger cost and possible adverse affects on plant reliability (NASA-Lewis 1980). Developing recuperators and ducting capable of operating reliably at high temperatures would reduce the fuel consumed during combustion and thereby enhance the attractiveness of high-temperature power conversion systems.

Fuel Gas Cleanup Systems and Coal Gasifiers

Increasing the heating value of gasified coals and enhancing the removal of tars and particulates that impose thermodynamic penalties are important to the developing gasifier combined cycle systems and molten carbonate fuel cells.

DC to AC Energy Conversion

Reducing the cost of DC to AC inverters from 50 $/kW is critical to the acceptance of DC generators such as fuel cells and thermionic converters.

Working Fluids for Bottoming Cycles

Working fluids are currently the major limiting factor in using higher temperatures in bottoming cycles. Several studies that have been conducted have surveyed available fluids, but little research has been directed at developing working fluids that would be useful both in bottoming and in heat pumps. Organic fluids with desirable properties are capable of operating up to

250^{0}F to 300^{0}F, but become unstable at higher temperatures. Toluene, a widely used organic fluid, is stable up to 750^{0}F, but is also highly flammable and possesses a very low vapor pressure.

Research in this area should be directed toward developing a fluid with the following characteristics:

- stable at high temperatures (e.g., 800^{0}F)
- noncorrosive
- nonflammable
- nontoxic
- high latent heat.

Concern has been expressed that such an ideal fluid might only be found after an expense that the market would not justify.

Cogeneration technologies have received a great deal of attention from both the government and the private sector. DOE programs include the following:

- Integrated Coal Conversion and Utilization Systems (ICCUS) - ICCUS is investigating fluidized beds, direct combustion and coal gasification.

- Advanced Cogeneration Systems (ACS) - ACS is investigating a range of advanced technologies, including externally fired gas turbines, Stirling engines, direct-fired gas turbines and diesel engines. They are also investigating fuel specifications for coal-derived synfuels and they expect to produce a full-scale demonstration by 1985. The objective of ACS is to permit efficient, reliable and clean operation on minimally processed, lower grade heavy petroleum fuels.

- Heat Recovery Component Technology (HRCT) - HRCT focuses on the recovery of low-grade waste heat, which includes organic Rankine cycles and heat exchanger improvements in, for example, the areas of fouling and corrosion.

In the private sector many companies are involved in various aspects of cogeneration:

- Westinghouse
- General Electric
- Thermo Electron
- Carrier

- Sunstrand
- MTI
- Garrett AiResearch.

Cogeneration has experienced decades of institutional barriers that have contributed to its current low level of use. The recently enacted Public Utilities Regulatory Policies Act (PURPA) has removed several important disincentives. Plants qualifying under the PURPA guidelines are guaranteed that the utilities must purchase excess electricity, pay a reasonable price for the electricity, and supply cogeneration facilities with backup electricity on a nondiscriminatory basis. These regulations both guarantee the availability of a reliable backup source and enhance the economic appeal of cogeneration.

Although the major disincentives to cogeneration have been addressed by PURPA, a few nontechnical barriers remain:

- the uncertainty attached with unproven, undemonstrated technologies
- capital shortages
- the high return on investment and short payback time required of major investments.

In terms of technology requirements, much of the conservation retrofit can be achieved without government assisted R&D. Technical impediments do exist, such as process retrofit problems and the use of "package boilers," which cannot be retrofitted to coal and which produce steam at too low a temperature and pressure for topping. The need for federally assisted R&D lies in accelerating the fuel switching capability of cogeneration through developments in alternate fuels use.

As a result of cogeneration's wide publicity over the past several years, much of the necessary research for long-term penetration appears to be covered by both government and private programs. Possible appropriate areas of federally supported research include developing high-temperature organic bottoming fluids, supporting heat exchanger development for high-temperature corrosive environments, and enhancing the alternate and low-grade fuels capability of cogeneration systems.

5.4.4 Industrial Systems Controls and Sensors

Systems controls date back to the late seventeenth century, when the Watt governor was applied to steam engine control. Control theory gradually progressed after this until World War II, when control of weapons systems provided the impetus for a phenomenal growth in both control theory development and application. After the war, automatic control systems became increasingly integrated into many types of dynamic systems. Progress was accelerated on one hand by the development of computers for direct control purposes and on the other by the application of controls in the aerospace industry (Rabbins et al. 1980).

Systems controls have already found many successful applications in the manufacturing industries. Improved control over industrial processes has played a significant role in increasing the energy efficiency of many industries. Rising energy prices provide an incentive for the manufacturing industries to seek out additional applications of systems controls to conserve energy. The incentive is heightened by the fact that improved controls can also lead to higher labor and capital productivity, as well as improved safety and reliability. These nonenergy benefits of systems controls may be the primary reasons for their application in some industries, with energy savings being a welcome secondary effect.

In the short term, application of existing system control technologies offers substantial energy savings. These technologies are already being used in industry and do not require government support. In the mid-term, the most pressing technology need is in measurement technology because control theory has outpaced the ability to measure critical state variables with the necessary performance, reliability, and cost. Thus, research in the sensor and measurement field will have broad impact. In the mid to long term, research into systems theory and modeling, leading to a true large-scale systems theory and a general modeling theory, offers the potential for more sophisticated automatic controls and additional energy-efficiency improvements.

The potential energy savings from implementing a systems control technology can be substantial. For example, on-line chromatographs in distillation columns are reported to save 10 to 20% of the energy used in distillation processes (Griffin and Webb 1978). Since distillation processes account for approximately 3% of the nation's energy use, a maximum net total savings of 0.24 to 0.48 quads will result from application of a single technology.

Estimating the energy savings beyond that which would occur in the absence of research on systems controls is a more complex problem than estimating the savings from a single technology. One reason for this complexity is that systems controls techniques developed for one application frequently find several other applications. Predicting these secondary applications to consider them in calculating the conservation potential of the research is extremely difficult. A group of systems controls experts estimated that implementating a broad set of research activities in the systems controls area would result in a 1.0 to 10%, or 0.8 to 8 quads reduction in national energy (Rabbins et al. 1980b). These numbers are simply educated estimates and should not be construed as accurate projections. However, they do indicate that systems controls research offers significant energy conservation potential in the industrial sector.

Because control theory has advanced more rapidly than measurement techniques, the earliest benefits from systems control research will most likely come from research into sensors and measurement methodologies. Improved sensor technology would facilitate the use of more sophisticated control methodologies that are presently impractical due to limitations in the ability to measure key parameters. Research could also advance systems and modeling theory. The energy conservation benefits from this research would probably be realized in the longer term. Therefore, research into sensor technology is considered to be a high priority component of an applied research agenda for the systems controls area.

The following discussions of research opportunities in the systems controls area are largely based on the proceedings of a DOE workshop on process and systems dynamics and control. The proceedings and the subsequent analysis of the workshop provide a much more detailed examination of the research opportunities relating to the systems controls field (Griffin and Webb 1978; Swets and Zeitlinger 1972). Research into sensors and measurement methodologies is emphasized in the following discussions because of the relative urgency of this work. However, other research opportunities in the systems controls field are also covered to accurately represent the scope of systems controls research that could be pursued to promote industrial energy conservation.

Measurement Technology

Measurement technology consists of sensors and measurement methodology. A "sensor" is a physical device that produces a signal with a known relation to one or more system variables. A "measurement methodology" refers to the process by which the system variable is measured and the signal converted to usable form. Although dramatic improvements have been made in measurement technology, mostly as a result of work on military and aerospace systems and, more recently, research into process control and air emissions control, the need for further developments is pressing. Several factors make measurement technology a particularly fruitful research area:

- An acute need exists for on-line instrumentation for use in real-time optimization and control of processes and energy systems. In many cases the necessary sensors are not available at any cost, while in others the existing sensors are too expensive, bulky, unreliable, inaccurate, or have poor dynamic response.
- The payoff is high for new sensors and measurement methodology because this technology permits substantial energy savings without a major capital investment. Improved measurement capability will allow the existing system to operate closer to optimum energy efficiency.
- The rapid advance of microprocessor technology and other micro-level solid-state devices provides numerous opportunities for integrating computation and data processing into sensors, thereby creating a new generation of intelligent sensing devices.
- New developments in micron-level large-scale integrated circuits, solid-state sensing elements, imaging technology, pattern recognition, and signal processing offer huge potential for the development of rugged, low-cost, high-performance sensors.

Given these advantages of measurement technology research, the panel of experts in the DOE workshop identified six highest priority areas of research opportunities relating to the industrial sector (Rabbins 1980):

- smarter sensors
- instrument performance
- flame quality sensors
- fuel analysis sensors
- pollutant and stack gas measurement systems
- harsh environment measurements.

A "smart" sensor has built-in signal processing or computational capability (including memory) and can accurately report an engineering variable under varying conditions, external disturbances and noise. Smart sensors can be self-calibrating. Research leading to smart sensors should include identification of new physical sensing principles, signal processing, and microprocessor technology needed to convert sensed phenomena to state variables in real time. Smarter sensors would not only provide potential energy savings in almost all manufacturing industries, but would also lead to materials savings, and improved product quality, productivity and maintenance.

Research into instrument performance is needed to improve the instrument's accuracy, repeatability, reliability, speed of response, and ability to reject noise and external disturbances. In industry more reliable on-line gauges, such as moisture gauges for drying processes and flue gas analyzers for furnaces, are needed in process control. Improvements in instrument performance can lead to significant energy-efficiency improvements. For example, a 1% improvement in moisture control on paper-making machines has lead to an 8% reduction in steam requirements (Swets and Zeitlinger 1972).

In multiburner furnaces optimum energy efficiency requires the fuel/air ratio to be near stoichiometric at <u>each</u> burner. Presently, optimization methods are based on combined effluents and are not adequate to insure stoichiometric mixtures, particularly when burners are not balanced with each other. Research is needed to measure the efficiency of one burner relative to another. Possible approaches include infrared, microwave, ionization, or acoustic flame quality sensors. Since multiburner furnaces are common in central power stations and industrial and marine power plants, the potential application of such research is large.

Fuel analysis sensors are needed to measure the chemical composition of fuels, particularly heating value (enthalpy of combustion). Presently, no real-time, on-line gauges of moderate accuracy and cost exist to make this measurement and therefore feed-forward controls to optimize fuel/air ratios and combustion efficiency cannot be implemented. Such feed-forward controls will become particularly important as the rising energy costs lead to frequent changes in fuel mixtures. These controls would permit optimum substitution of low-quality fuels (e.g., bark, low-Btu gas, etc.) for oil in a wide range of industrial processes.

Research leading to sensor systems for on-line measurements of pollutants in combustion exhausts is needed. The sensors must be rugged and resistant to harsh environments. To be used for control purposes, they must be reliable, since a hazardous condition may result from failure. The results of this research will permit fossil fuel combustion systems to combine optimization of energy efficiency with adequate pollution control.

Research is needed on improved sensors in harsh environments, including combustion, high temperatures, corrosive environments, and severe vibration. The variables most commonly requiring measurement are pressure, temperature and mass flow rate. In many cases, materials research is important to the development of suitable sensors. Other research could involve use of physical phenomena that are inherently resistant to harsh environments (e.g., fluidic sensors using the working fluids of the process) to measure or estimate the interest variable.

Systems Methodology and Modeling

Research into measurement technology offers the shortest term payoffs of the potential research areas in systems controls. However, longer-term improvements of automatic control systems will require further research into the systems methodology and modeling aspects of systems controls. The research opportunities that offer the most potential for energy conservation are briefly summarized below.

Improved methods for optimizing large and complex systems are needed. Existing control theory is most effective for systems with five to fifteen state variables. Energy systems are often too large in scale to be effectively analyzed and controlled using existing mathematical tools. Although a true general systems theory probably lies in the future, several areas offer research opportunities now. Research into hierarchies of computers--micro, mini, and macro--is needed to provide integrated control systems for industrial plants. Research into improved resource models, which take into account conflicting objectives and can incorporate sociological, technological, political, and economic factors, is needed. An improved optimization methodology for solving large-scale energy cycle problems with integer variables and general nonlinear constraints is needed. Stochastic optimization to handle uncertainty would have broad use in industrial resource management. Research into methods for computing the best tradeoff solution in a multiobjective optimization problem is important to the development of industrial strategies that satisfy the objectives of energy efficiency, environmental quality, productivity, and product quality.

Research opportunities that specifically address the need to improve modeling methods include the study of a methodology for developing, comparing, and verifying models for complex systems, leading to a general theory of modeling, and development of methods for computer-based interactive synthesis of models. A specific modeling research opportunity that would have an important impact on energy conservation is development of models for fossil fuel conversion and utilization systems. In particular, areas in which modeling could improve energy efficiency include coal conversion, which includes combustion, gasification, liquefication, and pyrolysis; oil production and refining, in which modeling, optimization and control could reduce energy and resource losses; and waste use, which entails improving the design and control of biomass and other waste processing schemes.

Research opportunities also exist for improving the methods with which systems and modeling theories are applied to real world control problems. A promising area from an energy-efficiency standpoint is on-line optimization and control. While much optimization and control theory exists for models with constant parameters, controls that are suitable for time-varying parameters are not well developed. In addition to improved sensors, which are discussed above, the research goal in this area would be to produce more sophisticated controllers. These controllers could be robust (i.e., environmentally insensitive), or adaptive (e.g., based on feedback or "self-tuning" schemes). Robust controllers will most likely be attractive when inexpensive controls are necessary, such as in automobiles, while adaptive controls are apt to find application in larger, more complex industrial energy systems. A good example of an industrial process where an adaptive control technique has energy conservation potential is in distillation columns. In a distillation column, the steam value for the reboiler will interact with controllers for steam flow rate, column pressure drop, column pressure, base temperature, column feed rate, column base level, and bottom flow rate. The multivariable adaptive control problem presented by distillation columns is common to industrial processes and therefore warrants research attention.

To take maximum advantage of the benefits of automatic controls, the system should be designed with the controls in mind. Presently, industrial systems are designed on the basis of a steady-state analysis, which does not necessarily lead to optimal performance under dynamic conditions. Thus, research into the simultaneous design of plant design configurations and control systems for major energy-consuming industrial processes could significantly improve the energy efficiency of these processes. The chemicals industry has already begun integrating control systems into their plant design process, and other opportunities exist in the manufacturing sector. A survey of the relative sophistication of the automatic control techniques used by various industries would be very illuminating.

The federal government has supported systems controls through the National Bureau of Standards, primarily in the area of measurement technology. In considering additional support of this area, the government should survey the large amount of private research that is being conducted on systems controls. Both vendors of computer equipment and industrial users of the equipment are actively involved in developing automatic controls. Although accurate information about state-of-the-art technologies in this rapidly advancing field is difficult to obtain due to the proprietary nature of many of them, some form of survey must be compiled prior to federal involvement to avoid duplication of effort.

The energy conservation potential of systems controls is substantial. Not only are systems controls relatively free from negative side effects that could impede their use, they frequently offer increased capital and labor productivity, improved safety and reliability, and higher product quality. Because systems controls do not generally involve massive capital investments, they tend to be economically attractive to industry. Thus, R&D on systems controls seem to have a high probability of finding application in industry and ultimately producing energy savings.

Because of the high potential payoff, the private sector will support research in the systems controls field. The important question is to what degree the potential energy savings from systems controls will occur as a result of private sector research in the absence of additional government support. The panel of experts at a DOE workshop estimated that systems controls research would result in annual energy savings of 0.8 to 8 quads. However, they did not attempt to estimate what portion of this research will likely be performed by industry without government support. To formulate an appropriate federal research agenda from the research opportunities that are identified above, the opportunities that are unlikely targets for private research funds should be chosen and justified. Technologies that are generic to many industries, such as sensors and general systems theory development, do not seem to be overly attractive to any one industry and therefore might be appropriate areas for federal funding. Industry-specific controls, however, are probably best left to private research programs.

5.4.5 Scrap Recycle

Recycling is the recovery of material for reuse either in its original form or in a reconstituted form (Barton 1979). Major sources of recyclable material are, in order of decreasing scrap quality, primary material production, manufacturing, obsolete products and municipal solid waste (MSW). In general the lower the material quality, the more expensive it is to reprocess into its original form and the more likely it is to be used in degraded form (e.g., cheap alloys, fillers, landfill, or burned for energy). Recycling is practiced only when the recycled material is cost competitive with a primary material and an assured supply of the recyclable material exists.

Although recycling is practiced as an economic, material-conserving activity, considerable energy savings are possible when little energy input is required to reconstitute the material. For example, the energy savings from production of aluminum, steel and paper from secondary materials rather than virgin ores are 95%, 60%, and 70%, respectively. The theoretical recoverable energy from MSW in 1980 was estimated at 1.6 quads (Rofe et al. 1978). In addition, recycling could provide an estimated 40% of the materials requirements for manufacturing (metals, glass, plastics, fibers, and rubber) (Boyd 1976). MSW recycling and energy recovery are receiving considerable attention from government programs under the Resource Conservation and Recovery Act of 1976 (Office of Solid Waste 1979; Mitre Corp. 1979; and Max 1979).

The energy saved by using secondary (recycle) rather than primary material sources is not precisely known (Bever 1977). Wilson (1979) has estimated the energy conservation through recycling of steel, aluminum, copper, zinc, lead, glass containers, and paper in the United Kingdom. Wilson first estimated energy saved per ton of material by recycling rather than using virgin materials (i.e., minerals, trees). Then, for each material he estimated the percentage of consumption potentially obtainable from recycling. From that percentage he subtracted the percentage currently recycled to obtain the additional percentage potentially recyclable. This latter figure was multiplied by the annual national consumption for the material and the energy savings per ton of recycled material to arrive at a potential additional energy savings from recycling each material. The sum of the energy savings for all the materials accounted for was 0.34 quad or 3.9% of the total United Kingdom energy requirement in 1977.

Industrial activity in the U.S. parallels that in the United Kingdom. Therefore, the energy savings potential of additional recycle can be roughly estimated at 3.9% of the U.S.'s total energy requirement, or about 3 quads/year. The realistic economic potential is somewhat less than 3 quads/year, but including other materials such as plastics, may offer additional potential. Maximum total savings are probably in the range of 2.5 to 3.5 quads per year. Once new technology is in place to realize these savings economically, the savings may not be fully realized for 5 to 20 years, depending primarily upon how compelling the economics of recycle prove to be.

Recycling has several common problems, including detection, classification, and separation of materials (Albert and Bolcyak 1980). Low-cost, energy-efficient methods for performing those functions are needed. Another approach to materials energy conservation is increased product life, but this approach has limits, such as when the societal need for a product changes (Fornerod 1977). Some of the many potential research opportunities are discussed below.

Aluminum scrap will become available in increasing amounts and will most likely saturate the current market in aluminum castings. To use increasing amounts of recycled aluminum (in wrought alloys), new technology capable of eliminating impurities and unwanted alloying elements is needed. Such refining technology will most likely be highly innovative (DOE 1980b).

Increased use of steel scrap depends upon the ability to economically analyze scrap and to separate out high alloy steels (Bever 1977).

Methods to treat impure titanium scrap are needed for reclaiming scrap not suitable for direct remelting. One process appears economical, but the financial rewards anticipated are too small to justify an expensive development program without an industry-wide cooperative effort (EIC Corporation 1979). Presumably, government funding could catalyze such an effort.

Processing low-grade copper scrap by chemical reduction appears technically feasible. Such a process could reduce both the costs and the energy requirements of the conventional pyrometallurgical recycling technology (EIC Corporation 1979).

The development of technology to separate different types of plastics or to reuse mixed plastics is in its infancy. Recycling can save up to 80% of the material energy (Wilson 1979).

Steel-belted tires pose significant obstacles in recycling processes when size reduction is necessary. Further research may find belting material equal or superior to steel, but more compatible with the recycling of tire rubber (Purcell 1978).

Agencies and organizations such as EPA, Bureau of Mines, Department of Agriculture and the Amercian Society of Testing Materials, in addition to DOE, are conducting research in waste use (Rofe et al. 1978). Undoubtedly, most of these activities are associated with MSW. The Bureau of Mines has been particularly active in technology development for MSW, automotive and stainless steel wastes, etc. (Boyd 1976). Since 1965 both government and industry R&D has been stimulated by several acts, the latest of which is the Resource Recovery and Conservation Act of 1976 (Humber and Lingle 1977).

Compared to those agencies and organizations, the firms involved in providing disposal services, intermediate (scrap) processors, and the equipment manufacturers who provide hardware to the industry are relatively small and do not have a research tradition. With some exceptions these firms do little R&D, either in-house or by buying research support (Albert and Bolcyak 1980).

Information flow is essential to conducting research on waste materials recycling. Max (1979) presented a nationwide survey of resource recovery and waste reduction activities. The EPA reports their activities yearly (Office of Solid Waste 1979). The U.S. Bureau of Mines (1980) functions as the federal government's focal point for authoritative information on all aspects of the minerals cycle from resource development and recycling, for all important minerals and mineral-based materials. The report further discusses the relationships among the Bureau of Mines, EPA, the Department of Commerce and DOE.

Scrap recycle appears to be well covered. Any additional involvement in recycling should be sharply focused in an area not already being addressed. Such involvement requires a more detailed survey of recycling research than has been performed here. Because the future potential of the waste utilization field is dependent upon the actions of several government agencies and private companies, uncertainty results that adds to the R&D investment risks (Rofe et al. 1978). Generally, various technologies are capable of performing a similar task in a given recovery problem. The market price and comparative processing costs will determine the particular process to be used. As conditions change, the optimum process may change to a different technology (Blum 1977). For example, government mandate or consumer initiative could bring about manned separation of waste in home and office and thereby obviate the need for certain separation technologies. In addition, some economic barriers and disincentives to recycling exist, such as freight rates and taxation, which discriminate in favor of primary production (Bever 1977). These risks may make private industry unwilling to support research on promising technologies and government research may be warranted.

5.4.6 Industrial Insulation

Industrial thermal insulation is used to control unwanted heat flows in all temperature regimes: cryogenic (-270^{o}C to -100^{o}C), low-temperature (-100^{o}C to 100^{o}C), intermediate-temperature (100^{o}C to 500^{o}C) and high-temperature (greater than 500^{o}C). These temperatures regimes, although somewhat arbitrary, represent the range of use of many commercially significant insulations. Industrial insulation is used on pipes and ducts for chemical processing and steam transmission, in metals, glass, heat treating, and calcining furnaces, on heat exchangers, and in many other applications. Some basic objectives of thermal insulation are maintaining the temperatures necessary to conduct the process, conserving process energy and helping maintain comfortable temperatures in the working environment.

The choice of materials and the physical design for insulation depend upon the temperatures, pressures, and chemical environment (corrosiveness) present in the intended application. As a result, a wide variety of ceramics, minerals, glasses, polymers, and metals is used. Thermal insulations may take many forms such as rigid or flexible sheets, fibrous blankets, batts and felts, loose fill, reflective sheets, foamed glass, insulating brick, and foamed polymers.

One study estimated the potential energy savings through the effective use of insulation to be about 1.5 quads per year for the six largest energy consuming industries, which accounted for about 75% of all industrial energy used in the 1971 to 1974 period (Donnelly et al. 1976). The estimated potential was based on technology available in 1975. Additional energy savings due to improved technology will probably be somewhat less than this, about 0.25-0.5 quad. Fuel savings will most likely follow the general industrial use pattern, that is mostly natural gas with lesser amounts of coal, oil, and electricity. The time for new technology to saturate the market depends upon the life of existing insulation and equipment replacement rates, but 10 to 20 years is probably a reasonable estimate.

The above conservation potential was based on Reding and Shepard (1975), who estimated the total rejected heat in the steel, aluminum, chemical, petroleum, paper, stone-clay-glass-cement, and food industries to be 12 quads or about 56% of the energy used by these industries per year in the 1971-1973 period. Reding and Shepard (1975) further estimated the potential energy savings on the basis of short-term conservation measures such as design modifications, insulation and maintenance, process integration, waste use, and process, operation and market modifications. Approximately one third of the total potential energy savings, or about 1.5 quads per year, were attributed to increased use of insulation and improved system maintenance. The estimated savings include those expected from steam system improvement plus a 10% reduction in the fuel required for direct fired processes in each industry by increased insulation use. Fifty percent of the savings from insulation were estimated for steam distribution systems used in industry.

Selecting insulation types and thicknesses is based on economics and must consider not only the original insulation cost, but also the cost of fuel to make up thermal losses, installation and maintenance costs and the useful life of the insulation. Therefore, energy-use reductions can stem from lower cost (increases economic thickness), more insulative and more durable insulations that are optimally applied. Also, improved hot-wall refractories in metal (e.g., steel and aluminum) and glass melting furnaces would allow the insulation levels to be increased in those furnaces without accelerating corrosion of the refractory. With standard refractories increased, insulation causes higher hot-wall temperatures, which melts the refractories. The following are some examples of research opportunities.

Hot-wall refractories in steel, aluminum and glass melting furnaces are subject to the corrosive action of the melt. The life of the refractory lining is increased by underinsulating or in some cases water cooling the furnace shell; this practice lowers the temperature at the melt-refractory interface and substantially slows degradation of the refractory. Improved hot-face refractories would be required before additional thermal insulation could be used effectively. Several potential research activities are critical to the development of improved refractories: 1) basic studies of melt interaction with pure single crystal oxides, polycrystalline oxides, multi-element phases, and finally, commercial refractories, 2) development of improved binders, and 3) development of improved refractory compositions based on the findings of (1) and (2).

Better data on insulating properties are needed for more effective use of insulation. Very little data are available on insulation's long-term performance in actual conditions (e.g., wet or otherwise contaminated) over a wide temperature range. Realistic tests need to be developed to collect this data. Information from these tests would be highly useful for optimizing insulation application.

Improved vapor barrier systems are needed for use with low-temperature insulation to prevent degradation of insulative values. Prevention of water absorption is critical to maintaining effective economic insulation.

An improved rigid insulation should be developed for steam system applications. Both better mechanical properties (compressive strength, resistance to fracturing and dusting) and lower thermal conductivity are desirable. Due to the magnitude of steam line thermal losses stated earlier, improvements in this single insulation application could ultimately effect relatively high energy savings.

The American Society for Testing Materials (ASTM) is the focal point for developing standard insulation tests. As of 1976 the ASTM was reviewing existing thermal conductivity tests for possible improvement (Donnelly et al. 1976). The National Bureau of Standards develops standard reference materials for conductivity standards. Most research on insulation improvement is carried out by the insulation manufacturers in response to their perceptions of industry needs. As of 1976 manufacturers in the insulation industry generally felt that existing insulations were quite good and that increased use of these materials by their customers would offer the best immediate-term possibility for energy conservation. Some of the insulation manufacturers indicated that they actually had better insulations developed, but that market conditions had not warranted their introduction (Donnelly et al. 1976). The economic barriers to increased insulation use must be considered when selecting appropriate research projects in this area.

5.4.7 Separation (Distillation) Processes

The size of the topic of separation as well as the number of individual processes is staggering. The topic could be defined to include techniques that segregate rocks of various sizes by sifting with screens, separation of substances using membranes to separate various isotopes, laser and magnetic field separation, and many other processes. Because of the enormity of the field this section focuses primarily on the area of distillation and a process known as critical fluid extraction.

The separation process of critical fluid extraction involves several steps: 1) a solvent near its critical point (a fluid at a temperature and pressure at which the gaseous phase and liquid phase are identical, forming one phase) is introduced into a mixture to combine with a desired substance, 2) the solvent and desired substance are then separated from the original mixture, and 3) the pressure and/or temperature are changed, causing the solvent to vaporize with only the desired substance remaining in liquid form.

DOE (1980b) estimated that 2 quads of energy were consumed in 1976 for distillation processes. Recent reports indicated that the energy consumed by distillation could be decreased by roughly 10% (DOE 1980b; Mix et al. 1978). This energy reduction is possible by using current technology to improve several areas:

- operating practices
- maintenance practices
- proper insulation
- waste heat recovery
- tray retrofitting
- instrumentation and control systems
- use of intermediate reboilers and condensers.

Because distillation is a very broad field, many potential energy conservation options exist. The conservation areas provided in the literature for distillation processes tend to be engineering application type processes, which require limited R&D.

Use of the critical extraction separation process to replace conventional "dual distillation of ethanol" appears to have significant energy conservation (DOE 1980a; Parkinson 1981a). A recent SERI/DOE report indicated that by the year 2000, between 24 to 42 billion gallons of ethanol will be produced as alcohol fuels from biomass (Parkinson 1981a). Based on these figures, an estimated energy savings between 0.5 to 0.8 quads per year in the year 2000 could be realized using critical fluid extraction and CO_2 as a solvent. In the year 2000 savings between 0.6 to 1.0 quads per year are estimated if an optimum solvent were developed for the process. Development of this critical fluid extraction process, to be used in producing fuel grade ethanol and in separating of other organic compounds, is almost solely dependent on research.

Significant energy conservation in the distillation type processes is expected to be attainable primarily through applied engineering, using current technology with little or no R&D. However, the critical fluid extraction separation process is still in its infancy and the energy conservation resulting from this area requires additional research.

DOE is currently funding a small pilot plant at the Arthur D. Little Company in Cambridge, Massachusetts. Research is currently needed in several areas:

- improving the solvent's distribution coefficient (maximizing the removal of the desired constituent)
- improving the solvent's selectivity
- developing or discovering better solvents
- identifying other areas in which similar processes could result in reduced energy consumption.

Development of solvents that are sensitive to molecular size as well as ion level is currently being investigated. Jack McDowell from Oak Ridge National Laboratory noted that energy conservation from this research area would result from having a lower cost of separating sensitive and critical materials from low-grade ore. No potential conservation estimates are currently available. Membrane filtration processes for use in concentrating products in the fruit and dairy industry also show potential for energy conservation, but again, no conservation potential estimate is currently available (DOE 1980c).

J. Douglas Way of the National Bureau of Standards estimated that use of liquid membranes is one novel membrane separation process that will require 30% less energy than distillation. This area appears to warrant further investigation as a potentially promising applied research area.

The technology associated with conventional distillation appears quite mature and thus research's potential impact on energy conservation appears somewhat limited. However, areas such as critical fluid extraction, other solvent extractions, liquid membranes, and magnetic separation process all appear to be areas in which research is needed to develop the processes to replace less efficient processes, thereby resulting in significant energy savings.

Robert Massey from DOE stated that over the past 3 years approximately $900,000 in funding has been provided by DOE, Office of Industrial Programs, on the critical fluid extraction process. This effort is currently being conducted by Arthur D. Little, Inc., and the National Bureau of Standards has supported a small effort on liquid membranes. These are promising research areas and, along with other identified promising separation technologies, should be seriously considered for continuing government research support.

5.4.8 Freeze Crystallization

Freeze crystallization, also referred to as extractive distillation, is a separation process in which a mixture is cooled, causing one component to crystalzize. The crystallized component is then removed, while the other remains in solution.

Because the crystallized substance is in a very pure form, the remaining solution becomes highly concentrated. This type of process is less energy intensive than the vaporization type separation process because, in general, the latent heats of crystallization are one half to one tenth those of vaporization. The freeze crystallization process may be used to desalinate water or remove water. The process is therefore applicable to concentrating pulp mill black liquor (waste stream resulting from the chemical separation of wood fibers), acetic acid, fruit juices, and dairy products.

A recent DOE report stated that the energy consumed by the U.S. by concentrating black liquor concentrate from the pulp and paper industry is about 0.2 quads, concentrating acetic acid 0.01 quad, and concentrating orange juice about 0.002 quad (Conservation Specialists 1979). In 1979, if absorption freezing were used to pre-evaporate black liquor for the entire current U.S. pulp production, an estimated 0.1 quad of energy could be saved. DOE also reported a significant energy conservation potential in the areas of refining acetic acid and in concentrating orange juice. Chris Eegan from Conservation Specialists in Andover, Massachusetts, reported that energy savings may also be expected in processes such as separating water from milk and whey.

R&D is currently needed to continue developing commercial process techniques for freeze crystallization of black liquor. For certain processes research is also needed to investigate benefits of nontriple point freezing to minimize losses of volatile gases.

Stanley Sobczynski from DOE's Office of Industrial Programs states that over the past three years his office has sponsored about $1,100,000 in research in the area of freeze crystallation. This effort, performed by Concentration Specialists Inc. of Andover, has culminated in the building of a pilot plant in Andover.

The technology of freeze crystallization does not appear mature and, as such, has many areas that need additional R&D. Identifying other industries that could use this technology once it is well developed also appears to be a necessary area for further investigation. A detailed study of the potential applications of freeze crystallization technology is recommended.

5.4.9 Catalysts

Catalysis can be broadly defined as a chemical process in which reaction rates are subjected to the influences of subtances that may or may not change chemically during the reaction (Perry and Chilton 1973). In practical terms, catalysts are useful for their ability to speed up chemical reactions. An important aspect of catalytic reactions is that when more than one reaction is possible, catalysts may selectively speed up one reaction more than others. This ability allows catalysts to reduce undesirable side reactions in chemicals manufacturing.

The transition theory view of the way catalysts work holds that catalysts reduce the potential energy barrier to a reaction by providing an alternate intermediate reactive complex for the reactants. Without the catalysts the reactants must form a high-energy intermediate complex before reaching the final state of products. This intermediate stage effectively forms an energy barrier to the reaction, which necessitates an input of energy to overcome. Adding a catalyst lowers this energy barrier and therefore reduces the required energy input.

Part of catalysts' conservation potential is related to their ability to increase the speed of a reaction. Increased speed means that, for the same production rate as a noncatalyzed reaction, the catalyzed reaction can take place at a lower temperature. Substantial energy savings are possible by lowering the process temperature.

Catalytic selectivity also is a major factor in catalysts' energy conservation potential. A catalyst's ability to favor a specific reaction is often the most important characteristic in catalyst selection. This ability is particularly important in processing organic chemicals, in which literally hundreds of side reactions may be possible. By increasing the yield of the desired product, the catalyst can dramatically reduce the net energy required per unit of product.

Catalysis is of major importance in chemicals and petroleum industry. According to one source, nearly 90% of chemical manufacturing processes currently involve catalysts (Kirk and Othmer 1978). Roughly 60% of the catalysts produced are used by the petroleum industry, with the remainder being used by the chemical industry.

Qualitatively, catalysts demonstrate a large potential for conserving energy. Both the petroleum industry and chemicals industry are substantial users of energy and catalytic processes. Improved catalysts could have major impacts on the energy requirements in both industries. Catalysts may also play a role in conservation by supplying efficient ways to meet pollution standards and in developing routes to produce new fuel sources. Several examples and case studies illustrating the energy conservation potential of catalysts are presented below.

Developing catalysts for processes not currently using catalysis, or improving catalysts used in present catalytic processes, can result in very large energy savings. For example, Riekert (1974) calculated the total energy efficiency of the old, noncatalyzed ammonia process as 17%. Development of the catalyzed process currently used increased the energy efficiency to 55%, or by roughly a factor of 3.

Use of catalysts in environmental control has been increasing in recent years (Kirk and Othmer 1978). As maintaining environmental quality becomes increasingly more difficult, catalysts may be used more to meet pollution standards while maintaining high levels of energy efficiency. Catalytic converters found in cars are an everyday example. Catalytic combustors are currently being investigated by the Environmental Protection Agency (EPA) and the Electric Power Research Institute (EPRI) as a method to control NO_x emissions in natural gas-fired burners. The catalytic combustors lower the combustors temperature by over 1000^oF and reduce NO_x formation by 90% compared to conventional firing. The largest problem with the process is the short lifetime for current catalysts (Parkinson 1981b).

Catalysts may also play an important role in developing alternative fuels. Catalytic fuel synthesis from coal and oil shale is thought to hold tremendous potential. Catalytic coal gasification has been studied by DOE and holds promise. Catalytic fuel cells may someday come into widespread use (Kirk and Othmer 1978). In a fairly recent development, scientists at Mobil have developed a catalytic process to convert methanol into gasoline and water. Eventually, a catalytic process to convert hydrogen and carbon monoxide into long-chain hydrocarbon fuels may be developed (Parkinson 1981b; Business Week 1981).

A quantitative estimate of the conservation potential of improved catalysts is difficult to make. A well-justified number would have to evaluate the efficiency and use of current catalysts and compare this with projected properties of new catalysts. Much additional work is needed to arrive at such an estimate. However, to provide a very general idea of how much energy could be saved, a rough calculation is given below.

The chemical industry used 1895.6×10^{12} Btu of energy for direct heating and process steam generation in 1974 (DOE 1978b). This energy was used to provide high-temperature environments for chemical reactions, distillation, drying, and other processes. By lowering the energy barrier to chemical reactions and by increasing yields, catalysts can reduce these energy uses. The above examples indicate that improved catalysts could save an average of between 10 and 50% of the steam and process heat energy used in chemicals production, or an energy savings of 0.18 to 0.95 quads per year. Additional energy savings would be possible through applications in the petroleum industry and in emissions control in transportation and industry.

In the long run, the most important role of R&D toward realizing energy conservation from catalysis is to increase the understanding of catalysis. As previously mentioned, today's catalysts are usually selected using an empirical approach. When catalysts are better understood, they will be able to be engineered to behave in very specific ways. Basic research into the fundamentals of catalysis can be considered the key to helping catalysis attain its full potential. Research in surface science may be particularly beneficial (Business Week 1981).

Applied R&D is also important in developing catalysts for processes that have not previously used them. For example, catalysts could be used for environmental control and production of alternative fuels by catalytic routes.

The areas described above are so broad that specific research opportunities within the areas could not be determined in this brief overview. The field of catalysis encompasses nearly all of the chemical and petroleum industry and has potentially broad implications in alternative fuels development. A much more detailed examination of the field would be required to determine both potential research opportunities and the level that these opportunities are being met with existing programs. Such a study could catalogue high-temperature processes and processes in which present catalysts are particularly inefficient. Developing new catalysts for such processes would offer increased productivity, as well as energy savings.

Although catalysts are a very promising energy conservation technology and significant research opportunities remain, this is an area that should be cautiously entered by the federal government. Because of a company's ability to patent a catalyst or to maintain a proprietary process, private industry has a large incentive to do research toward developing catalysts for existing processes. Thus, government supported research of new catalysts development is generally not appropriate. More appropriate would be federally supported research into the basic mechanisms associated with catalysis and an analytical survey of chemical processes to identify a systematic set of target areas for private industry to address in their research efforts.

5.4.10 Drying Technologies

Drying processes account for approximately 5% of the energy consumed in the industrial sector or about 1.4 quads per year (Reay 1978). Materials requiring drying can be roughly divided into four categories: block, sheet, fibre, and particles. Examples of block materials include brick, timber, and ceramics. Sheet materials include paper, board, and film; fibres include textiles and synthetic fibres; and particles include detergents, polymers, pigments, fertilizers, foods, and pharmaceuticals.

The diversity in applications and in the properties of the materials being dried provides a wide variety of methods and devices. Methods and devices commonly employed include spray drying, vacuum and freeze drying (microwave), infrared drying, fluidized bed drying, and superheated steam drying.

The technology intensiveness of drying processes varies substantially. In certain low-technology applications, such as grain drying, high technology solutions are unlikely to experience penetration. Major energy savings can also still be achieved through better housekeeping of older equipment.

Most of the drying techniques in use have been selected from empirical iteration. Fundamental characterization of the processes is still largely an open question. Although basic drying studies are under way nationally and internationally, the industry does not have a single coordinating body analogous to the Heat Transfer Research Institute or the Electric Power Research Institute. Coherence to the field's many disparate elements is thus needed to identify areas in which generic drying research will be most significant.

The principal consideration in selecting a drying method or device will be product quality. Hence, energy-conserving techniques will only be accepted if the quality of the product will improve or remain unaffected.

According to statistics from Oak Ridge Associated Universities (1980), drying and predrying were responsible for 9% of agriculture's energy consumption, or 0.105 quads/yr in 1974. Drying consumed 63 x 10^{12} Btu/yr in food processing. In the textile industry drying and predrying consumed 24% of the energy used in wet processing, or 51 x 10^{12} Btu/yr. In paper and pulp, pulp and board processing accounts for 80% of the industry's energy, with drying the major energy-consuming step. Pulp drying consumed 11 x 10^{12} Btu/yr in 1974.

Data for drying in other industries are much less complete. In the cement industry, the drying of Portland cement and brick consumed 30×10^{12} Btu/yr. Data for other segments of this sector are not as readily available.

Current dryers typically operate with a thermal efficiency of 50% and energy represents approximately 60% of the total drying cost. The best dryers available have an efficiency of 80% and the worst have an efficiency of 20%. However, these efficiency figures are only very general and only meaningful when considered with specific product quality constraints.

A very rough estimate of the energy savings from improved drying technologies can be made by assuming that the industry-wide average efficiency of drying can be increased from 50% to 70 to 90%. If R&D could increase the average efficiency of dryers throughout industry to 70 to 90%, roughly 0.4 to 0.6 quads per year would be saved.

Research efforts that will have significant energy impact are difficult to assert because of the diversity of processes and their specific requirements. Many elements affect the drying of a material (Mujundar 1980):

- physical appearance (cake, powder, grain, slurry, ...)
- material properties (specific gravity, density, hygroscopicity, ...)
- thermal properties (specific heat, heat sensitivity, ...)
- drying characteristics (drying rate curves, equilibrium moisture, ...)
- physical structure (porosity, pore size distribution, ...)
- special characteristics (migration of chemicals, agglomeration, ...)
- hazards (toxicity, explosion, ...).

Future developments that significantly impact drying are likely to be revolutionary, requiring substantial process change. Dry processing, accepting wetter products, heat pumps, and vapor compression are examples of revolutionary techniques. Dry process routes are clearly a way to eliminate drying stages. Cement is currently processed via this technique. Accepting wet products would also allow a reduction in drying intensiveness. Foods and detergents are products that may fall in this category (Reay 1978). These two changes are clearly process specific and product quality will certainly be of major importance. The diversity and specificity of drying routes suggest that development should be left to each industry.

Vapor compression and heat pumps, on the other hand, have generic applications. Vapor compression presents formidable capital and compressor design problems and possesses few advantages over the use of a heat pump.

Heat pumps coupled with solar energy are already experiencing penetration in corn and grain drying. As higher temperature and more economical capabilities are developed, applications can extend to drying in all sectors. Details of applicability are sparse, but this technology appears to have potential to significantly contribute to energy conservation in drying.

In addition to revolutionary developments, the drying industries have pointed to the need for increased fundamental research of processes in dryers (as opposed to fundamental studies on drying). For example, transport coefficients need to be determined to predict drying rates and energy efficiency in paper and pulp drum dryers, which are still used for 80 to 85% of the drying operations. These efforts would also be very process specific and better left to industrial discretion.

Other topics that have promising applications include centrifugal fluidized bed dryers and microwave technology for freeze drying. Centrifugal fluidized bed dryers have been shown to dry foods five times faster than conventional methods due to much higher heat-transfer coefficients (Lazar and Farcas 1980). Efforts in this area are still needed to clarify the mechanics of heat and mass transfer and to determine pressure drop and fluidization characteristics of different bed materials. This technology also has applications in other areas, such as coal drying.

Microwave drying also appears to have energy conservation potential in the paper and food industries because of microwaves' penetrating characteristics and the high concentration of energy achievable. An interesting problem encountered in food drying is microwave breakdown. Breakdown occurs because the optimum frequency for drying is very close to the collisional frequency of the gas, inducing a resonant effect that strips electrons from the gas. This creates an ionic medium that blocks the penetration of microwaves, resulting in breakdown (Aroem and Ma 1980).

Because many developments in drying are proprietary, the extent of industrial research activities is difficult to assess beyond a broad identification of such activities in all utilizing industries.

DOE has been involved in several near-term drying projects, principally in the agricultural, textile, and paper and pulp industries. In the agricultural sector efforts have been aimed at reducing the energy consumed in corn and grain drying. Projects sponsored through the Office of Industrial Programs include microwave-vacuum drying, electric heat pump drying, and the use of a liquid dessicant for corn drying. Crop drying is also a common subject of research in the agricultural schools of universities such as U.C. Davis, Cal Poly, San Luis Obispo, Michigan State University, and the University of Minnesota. The Office of Industrial Programs has also sponsored a dry-processing study in textile texturing and several technology demonstrations in paper and pulp, including the use of mechanical dewatering, multi-deck dryers, and a mach nozzle. The DOE projects and other published literature to date have focused on near-term possibilities. Effort in post-1990 technologies appears to be essentially nonexistent.

A general lack of information in drying technologies and processes is a major barrier to R&D. Drying methods frequently affect product characteristics and thus are often considered proprietary. An additional problem is the absence of a center to coordinate information on the wide breadth of national and international drying research activities.

From this brief overview an appropriate role for the federal government in drying technologies research appears to involve two functions: 1) the government should monitor ongoing research in drying technologies with an eye toward identifying promising research areas that are not being covered by the private sector, and 2) DOE should act as an information clearinghouse by performing survey studies of technologies and conducting workshops and symposia on drying technologies.

5.4.11 Alternate Fuel Combustion

Alternate fuels comprise those fuels and fuel combinations that replace petroleum with domestically plentiful or renewable sources. Questions that need to be resolved to accelerate alternate fuel use include fuel characteristics, fuel/engine compatibility, and emissions problems. In addition, the fuel used should require a minimum amount of processing.

A salient example of such a fuel would be coal for producing industrial process heat, a need which currently consumes over 10 quads/year of petroleum

(Oak Ridge Associated Universities 1980). In boilers or direct-fired units in which the handling of coal may be uneconomical, coal slurries may provide an acceptable substitute. Research opportunities remain in employing both coal (e.g., pressurized fluid bed combustion) and coal slurries (e.g., coal/water and coal/methanol combinations). The coal utilization program of the DOE's Fossil Fuels Office is performing extensive work in this area and it is, therefore, not addressed in this study, except in the case where the fuels are combusted in engines. The alternate fuels considered here are primarily those which might substitute in industrial engines.

Industrial engines are typically characterized as heavy duty machines that are able to sustain long operating periods under severe and fluctuating loads and environmental conditions (Thomas 1980). Engine sizes typically range from 1,500 hp to 50,000 hp. Below 1,500 hp engines tend to require higher quality fuels such as gasoline. These smaller units will be considered in the section discussing alternate fuels in transportation.

Most industrial engines are used for either generating electrical power or driving machinery. Because these functions are generic, industrial engines are employed in most end-use sectors. Large transportation engines, notably railroad and marine engines, are similar in size and fuel requirements to industrial engines and are therefore included in this discussion.

Industrial engines consumed approximately 1.60 quads of petroleum fuel in 1974 (not including engines used in utilities) (Thomas 1980). Natural gas accounted for 0.86 quads and petroleum distillate 0.76 quads, of which 0.575 quads and 0.135 quads were consumed in railroad and marine engines, respectively. The use of residual grade petroleum in industrial engines is essentially nil (Thomas 1980).

If the alternate fuels are formulated for acceptance in current engines, their penetration would be limited by economics, availability, handling considerations, and other nontechnical issues. Cost is currently the dominant barrier to the alternate fuel use. An important goal in alternate fuels research is to use fuels with minimal processing to minimize cost. In coal-derived fuels, fuel cost rises sharply as a function of increased processing (Cart 1979).

Fuel/engine compatibility studies are needed to take greatest advantage of the lower quality fuels. If new engine designs are required, complete penetration of the alternate fuels could take 20 years, the average life of an engine.

To date, the research on alternate fuels that might be used in industrial engines has been focused on preliminary investigations. Studies have evaluated similarities and differences of proposed alternate fuels with conventional fuels. Fuel characterization and likely problems, such as excessive NO_x emissions from fuel-bound nitrogen, have been the primary thrust of recent work. Extensive R&D into alternate fuel combustion, particularly oil and shale distillates, has been hindered by the meager quantities available.

Long-term research is needed to enable use of low-quality alternate fuels and, thereby, to reduce the fuel cost. The traditional approach has been to study individual fuel/engine pairs, but this method may prove unacceptably expensive as the number of engines and fuels increases.

Fundamental studies are required to understand the mechanisms of combustion and the causes of pollution formation both in general and specific to fuels. With the increasing variety of alternate fuels, the basic studies will provide an understanding that may be applied to various engines and fuels. This ability would shorten the fuel/engine development time required for individual fuel/engine compatibility efforts.

In addition to these fundamental combustion studies, fuel/engine design optimization is needed. Preliminary work has indicated that injection pressure, injector location and size, and mixture turbulence will significantly affect efficiency and emissions in diesel engines (Thomas 1980). Research also is needed with coal and shale distillates and slurries. These fuels are discussed below.

Coal and Shale Distillates

Examples of problems that must be resolved to permit the use of low quality distillates in engines include the following (Thomas 1980):

- Engines must be capable of limiting NO_x emissions to an acceptable level. The fuel-bound nitrogen in shale and coal distillates is typically 100 times greater than in conventional fuels.

- Features such as improved cooling methods are needed to allow the use of fuels containing high levels of contaminants.
- Materials that are resistant to corrosive fuels need to be developed.
- Designs that would eliminate excess CO, unburned hydrocarbons, and smoke are needed to promote vaporization and complete burning.
- Rough combustion and cold-start problems due to the low cetane number characteristic of highly aromatic fuels, especially coal distillates, must be mitigated.

Slurries

Although coal currently appears to be the most attractive slurry solid (Ryan et al. 1980), cellulose and starch are also possible solids. Examples of research areas include the following:

- Atomization, injection, and particle-liquid interaction must be optimized to facilitate complete combustion. Soot, particulates, and unburned hdyrocarbons result from incomplete combustion of the solid components.
- Excessive radiation losses from the slurry solid must be controlled.

Gasified coal needs little or no development to facilitate direct replacement for natural gas. A near-term research need is mitigation of the slag formed by low Btu gases in turbines.

Another interesting concept is the combustion of pulverized solids such as coal in diesel engines. This has been shown to be possible with little degradation in performance (Ryan et al. 1980).

Although extensive, highly-funded work focusing on the development and processing of various alternate fuels has taken place, little research has been directed at the combustion of these fuels in industrial engines. The Southwest Research Institute in San Antonio, Texas, appears to be the primary center for engine combustion work. They have been involved in approximately 10 projects with DOE, each funded at 2 to 5 man-years per year. They have also been involved in several projects sponsored by the Department of Defense (DOD). However, most of their work for DOE and DOD has centered around transportation engines.

Several major uncertainties exist that could hinder alternate fuel penetration in industrial engines. The price and availability of traditional petroleum fuels are extremely difficult to predict and are critical considerations when assessing the attractiveness of alternate fuels to industry. The availability of fuels such as coal and shale distillates and the investment required for processing to satisfy the overall demand is equally uncertain and, as mentioned earlier, the sparsity of the fuels to date has inhibited combustion research. Changing environmental regulations will also affect alternate fuels development. Soot, particulates, and exhaust opacity are currently unregulated, but most likely will come under regulation. The 20-year lifetime typical of current engines will slow penetration if new engine designs are necessary to effectively use the alternate fuels. To reduce the processing required, additional R&D is essential. Without further work, the current cost disadvantage of alternate fuels will continue to prohibit penetration.

Research such as that under way at the Southwest Research Institute should be expanded to the fundamental studies mentioned earlier. In developing such a program the fuel and engine development should be combined as a single program because of the interrelationship between engine geometry and combustion processes. As a secondary effort, investigating innovative fuels such as coal dust in industrial engines may be worthwhile.

5.4.12 Genetic Engineering

Applied genetics comprises two biotechnologies: classical genetics, such as the breeding of microorganisms, and molecular genetics, which includes recombinant DNA techniques.

Microbes have been used in industrial processes for centuries. Fermentation has long been exploited to produce beer and alcohol. By the turn of the century the chemical industry began using fermentation to produce organic solvents and enzymes for treating textiles. Within the past decade, biotechnologies have experienced tremendous growth in the pharmaceutical industry, enabling the production of vitamins and new antibodies. These three industries, pharmaceuticals, chemicals, and food processing, have sponsored the bulk of applied genetics activities to date. The thrust of university research has also been toward health-related issues, due to both the tremendous potential and the funding biases of sponsoring government agencies.

Applied genetics, or more specifically, recombinant DNA, has experienced accelerated growth so recently that its full potential in these and other industries has not been thoroughly assessed. Both energy conversion and conservation appears promising for recombinant DNA technologies.

More economical conversion of biomass to hydrogen, methane, or ethanol is a promising application of applied genetics. In the organic chemicals industry this capability could aid in a transition away from petroleum, which accounts for 90% of all raw material used. Genetic engineering can also aid in reducing the energy requirements of separation processes such as distillation. Low-energy recovery of materials from waste streams is another form of separation with promise.

Advantages beyond energy conservation and resulting from the use of applied genetics include the use of renewable resources, less extreme processing conditions (e.g., temperature and pressure), the possibility of single-step processing replacing multi-step techniques, and a reduction in pollution.

The intermediate-term potential for industrial energy conservation through applied genetics appears small but this is largely due to the sparsity of information concerning possible applications. More complete information is necessary to assess the scope of applicable industrial processes.

Because growth in applied genetics is recent and therefore information describing the scope of industrial applications is lacking, the energy conservation potential is very difficult to assess. Many potential applications exist for genetic engineering. In energy conversion, the long-term potential for a fuel switch to biomass-derived hydrogen and methane may be significant since natural gas accounted for 7 quads of industrial energy use in 1979. Genetic engineering could produce organisms that convert biomass directly to hydrogen or methane. Another possible application area, distillation processes, consumes 2 quads/yr, but the fraction applicable to genetic engineering is yet undetermined. A raw resource switch from petroleum to biomass in the organic chemicals sector could potentially displace 0.1-0.2 quads/yr of petroleum.

An immediate research opportunity in applied genetics is the identification of industrial processes that can potentially employ genetic engineering.

Little work has been done outside of the pharmaceutical, chemical, and food processing industries in identifying applications, and almost no work has been performed in assessing energy conservation potential. Topics to be considered include process changes such as separations and material recovery, raw materials substitution as in the replacement of petroleum with renewable resources, and the energy conversion of renewable sources to hydrogen, methane, or ethanol.

If the energy conservation assessment indicates applied research is merited, problems to be addressed include the identification of genetic systems and vectors, mass production techniques, immobilization of the cells in the reactor column, and genetic mapping of the genes on the chromosomes.

The field of applied genetics has experienced rapid growth in the past decade with many small labs entering the field. The sizes of the labs vary from a handful of researchers to several hundred and include Bethesda Research Labs, Biogen, Cetus, Genetech, Genex, Molecular Genetics, and New England Biolabs. Large chemical firms are also developing in-house expertise in recombinant DNA. However, most of the current work is proprietary and little is directed toward energy conservation applications. Research pertinent to energy conservation thus appears negligible.

Because of the focus and profitability of applied genetics in pharmaceuticals and the university bias toward health-related research, government involvement is essential if genetic engineering is desired as a vehicle to aid in energy conservation and fuel switching. Because of the knowledge base that has been established through previous genetic engineering efforts, the government must coordinate any research program in this area with these efforts.

Significant nontechnical issues are certain to affect the acceptability and penetration of genetic engineering. Rapid change and growth and the newness of this field will undoubtedly elicit interest from a public wary of the effects of such developments on their lives. Important areas of public concern include potentially harmful effects on human health and the environment. This concern is amplified by the organisms' ability to reproduce, making their release difficult to control. Replacing diverse strains with a single genetically superior strain appears to counter nature's preference for diversity. Such strains may increase the sensitivity of living things, such as humans, to disease.

A third area of concern is the general philosophic question of the human role in controlling and creating life. Fears are certain to arise that progressive advances in genetic engineering will lead to genetic manipulation of higher order organisms and eventually humans. These issues will have to be resolved if genetic engineering is to achieve its potential as an energy conservation technology.

5.4.13 Tribology

Tribology is the science of friction, lubrication, and wear. As such it is applicable to energy conservation through reduction of energy losses in industry caused directly by friction and indirectly by wear, which requires replacement of worn-out equipment. One estimate in 1975 was that 1.3% of U.S. energy consumption could be saved by reduction of friction and wear in general industry (Jost 1975). About 10% of this savings was due to reduced energy cost of replacement parts.

Because the specific candidates for tribological improvement are too numerous and diverse to list individually, wear control information was proposed to be disseminated in a manner that would be useful to industrial designers (Pinkus and Wilcock 1977). This dissemination resulted in the ASME Wear Control Handbook (American Society of Mechanical Engineers 1980).

The primary industrial area identified by Pinkus and Wilcock (1977) for possible energy savings via tribology is the steel industry. As shown in Table 5.5, the steel industry is a substantial energy user and therefore constitutes an attractive energy conservation target. Also, the steel industry uses rolling and forming operations that require rather severe surface interactions between workpiece and tool. The product quality and energy intensity of these operations are strongly dependent on the metal working lubricant that is used.

Most of the metal forming operations (e.g., rolling, forming, stamping, drawing) are driven by electric motors. Approximately 13% of the energy used by the steel industry is electrical energy (Arthur D. Little, Inc. 1978), about 30% of which is apparently used in metal forming operations (Battelle-Columbus Laboratories 1975b). If 25 to 50% of this energy is assumed to be recoverable by improvements in metal forming processes and lubricants, then approximately 0.04 to 0.07% of total U.S. energy consumption or 0.3 to 0.5 quads are directly recoverable. (This calculation is based on the fact that the steel industry accounts for about 4% of total U.S. energy consumption.) These savings are substantially less than the 1.5 to 3% estimated by Pinkus and Wilcock (1977). The estimate made here does not take into account energy savings due to reduced need for replacement parts. However, indirect energy savings would not seem to be large enough to account for the factor of 2 to 4 difference between the two estimates.

A second important area for applying tribology to energy conservation is in steam turbines. Although steam turbines are primarily a utility technology, they are considered here because of the ease of technology transfer from industry to utilities.

Steam turbines accounted for 83% of electric power generation in 1976 (Pinkus and Wilcock 1977). The remainder was produced with gas turbines, hydro, and diesels. Steam turbines generally have about ten sleeve-type fluid film bearings and two thrust bearings with a journal 1 to 2 feet in diameter running at 3600 rpm. These bearings usually run in the turbulent regime, and sufficient friction exists to cause power losses of about 0.5% of plant output. Given the plant efficiency of about 33%, the energy lost is about 1.25% of the energy used in utilities or about 0.35% of total U.S. consumption. If 25 to 50% of this energy can be recovered through better bearing designs, 0.09 to 0.18% of total U.S. energy can be saved. About another 0.1% can be saved with improved gas path seals and control of blade tip clearances to prevent loss of working fluids. The potential energy savings through tribology in the industrial and utility sectors are summarized in Table 5.24.

The general areas of tribological research that apply to industrial energy conservation are discussed briefly below. These areas fall into the four basic categories of rolling contact, sliding (or abrasive) wear, lubricants, and materials. Because tribological research at the more basic levels tends to have rather broad applications, these research areas overlap a great deal with those identified in the context of transportation in Section 4.5.

Rolling Contact

Improvement is needed in the fundamental understanding of rolling (traction) contact among materials at high normal loads. This improvement essentially requires an advancement in elastohydrodynamic lubrication technology, in

TABLE 5.24. Energy Savings in the Industrial and Utility Sectors Through Tribology

Operation/Component	Percent of U.S. Savings	Energy Savings (10^{15} Btu)
General industrial wear control	1.3	1.0
Steel rolling and forming	0.04-0.07	0.03-0.05
Steam turbine bearings	0.09-0.18	0.07-0.14
Steam turbine seals	0.1	0.08
Total	1.53-1.65	1.19-1.29

which friction and film thicknesses are determined by the elastic properties of the contacting bodies and the viscous properties of the lubricant at operating pressures, temperatures, and shear rates. Advancements in rolling contact technology in industry would apply to the development of more efficient and durable large rolling element bearings for turbomachinery and the metal forming operations (rolling) in steelmaking.

Sliding (or Abrasive) Wear

Better understanding of fundamental mechanisms of wear particle generation and materials wastage in sliding or abrasive wear situations is needed. Applications of wear research include development of more durable industrial machinery to reduce down time, replacement costs, and loss of device power density and efficiency, and development of improved seals for use in turbomachinery, gas turbines, pumps, and compressors.

Lubricants

A wide range of new lubricants needs to be developed. In industry high-temperature lubricants (500-1100^{o}C) would be useful in industrial engines, particularly in adiabatic engines. Assessment of the degree and manner in which combustion products and process fluids can be used as lubricants in engines and bearings is also a promising research area.

Materials

New materials and coatings that are able to withstand high temperatures and operate in the absence of lubricants have potential use in foil-type gas bearings in turbomachinery. A babbit-type material capable of 220°C for sustained periods would also be applicable to turbomachinery bearings. A material with high fracture toughness and surface hardness, and resistance to surface fatigue is needed in high-speed rolling bearings, where failures can result in catastrophic results.

Table 5.25 summarizes in greater detail a list of recommended tribology research projects that apply to industry from Pinkus and Wilcock (1977). Many tribology research programs are already in existence. Table 5.26 summarizes some of the major efforts. However, this list is certainly not complete. Undoubtably, some relevant industrial research is not included in this table due to the proprietary nature of the work. However, Table 5.25 is considered to be a representative sample of current research.

Studies of basic friction and wear phenomena and mechanisms appear to be dominated by government sponsored projects in U.S. universities and laboratories, and by the National Tribology center in Risley, England. Lubricant developments are dominated by the large oil companies, since they have the resources, capabilities and potential markets to do so. New materials developments are occurring primarily by government sponsorship, although many industrial coating services are available. Development of specific devices that require tribology research, such as adiabatic diesels and aircraft bearings, is being addressed in industrial research programs, with government support in some cases.

As this section points out, the potential energy savings in industry from tribological research are significant. However, the applications and benefits from tribological improvements are not widely recognized in industry. Part of this information problem has been addressed by publication of the ASME Wear Control Handbook (American Society of Mechanical Engineers 1980). However, information gaps still remain. The federal government could play an important role in facilitating energy savings by undertaking activities to disseminate information concerning the possible applications of new tribological developments and efforts to enhance technology transfer among industries and sectors.

The federal government should also consider heavier involvement in fundamental tribological research. Because tribology is generally supportive of other technologies, it has historically been underfunded. Of the activities

TABLE 5.25. Tribology Research Projects (Pinkus and Wilcock 1977)

Application Area	Technology	Project Title	Estimated R&D Cost $/Yr Thousands	Estimated R&D Cost Years	Technical Feasibility	Economic Feasibility	Response by Industry and Public	Project Priority[a]
Power Generation	Low-Friction Turbulent Bearings	Water-Lubricated Bearings for Utilities	200	4	High	Medium	Low	
		High-Temperature Babbitt-Like Materials	100	3	Low	High	High	B
		Reduction of Power Loss in Turbulent Bearings	200	2	High	High	Medium	
		Mechanism of Turbulence and Inertia in Hydrodynamic Bearings	100	2	High	High	Medium	
	Gaspath Seals	Active Control of Labyrinth Seal Concentricity	100	4	Medium	Medium	Medium	B
Turbomachinery	Rolling Element Bearings: DN 3.0 x 10^6	Cage Design and Lubrication for Small High-Speed Ball Bearings	150	3	High			
		Development of Rolling Element Bearings Materials Having High Fracture Toughness	150	3	Low	Medium	Medium	B
		Analysis and Development of Cylindrical Roller Bearings for Three Million DN Operation	125	3	Medium			
		Tapered Roller Bearings for 3.5 Million DN	150	4	Medium			
		Series Hybrid Bearing	100	3	High			
	Process Fluid Bearings	Refrigerant Lubricated Bearings	100	3	Medium	Medium	High	
		Bearings for Oxygen Compressor Service	300	2	High	Medium	Medium	A
		Foil Bearing Materials	200	4	High	Low	Medium	
	Gaspath Seals	Abradable Blade Tips and Shrouds	250	3	Medium	Medium	Medium	B
		Active Control of Blade Tip Clearance	150	4				
Industrial Machinery and Processes	Wear	Mechanism of Foreign Particle Wear	100	5	Medium	High	High	A
		Wear Control Handbook	50	3				
	Metal Processing	Mechanism of Metal Rolling	100	5	Low	Low	Low	C
		Metal Processing	500	5				

(a) A represents highest priority, C represents lowest priority

TABLE 5.26. Summary of Existing Tribology Research Programs

	Project	Description	Funding/Source	Date	Location
1.	Two-phase turbines for efficient waste heat recovery[a]	Low-speed turbine for adiabatic diesel exhaust	100K DOE/BES	1980	Calif. Inst. Tech. JPL Pasadena D. G. Elliott
2.	Nondestructive evaluation	Development of testing methods for ceramics (cylinder walls, etc.)	185K DOE/BES	1980	Ames Laboratory Iowa State U. C. P. Burger
3.	Mechanical properties of ceramics	Study of toughening mechanisms in brittle materials, high-temp failures (cylinder walls, etc.)	190K DOE/BES	1980	Lawrence Berkeley Laboratory Berkeley, California A. G. Evans
4.	Changes in surface microstructure of super alloys caused by ion implementation	Study of surface modification treatments at T < 400°C (cylinder walls etc.)	56.7K NSF	1980	Dept. of Met. U. of Conn. D. I. Potter
5.	Mechanism of Deposition and erosion on bare, oxidized and oxidizing metals	Study of basic wear mechanisms	54.6K NSF	1980	Dept. Mech. & Aero. Engr. U. of Delaware J. W. Edington
6.	Study of surface layer damage due to indentation fatigue	Study of basic wear mechanism	61K NSF	1980	Dept. Mech. & Aero. Engr. U. of Delware F. G. Greenfield
7.	Wear and friction of metallic materials	Basic study of abrasive wear mechanism	75.8K NSF	1980	Dept. Met. Engr. Ohio State U. D. L. Rigney
8.	Principles of Metal Erosion Resistance	Basic study of erosive wear mechanisms	45.9K NSF	1980	Dept. Met. Engr. Ohio State U. P. G. Shewmon
9.	Role of Structure in the Wear Process	Basic study of wear processes	45.9K NSF	1980	Vanderbilt U. Dept. Mat. Sci. J. J. Wert
10.	Combustion Zone Duraability Program[b]	Identify limiting factors for combustion zone materials durability	1.81M DOE/Office of Coal Utilization	1980	Pacific Northwest Laboratory D. D. Hays
11.	Highway Vehicle Systems (Conference)[a]	Alternate designs, materials, and fuels for highway engines	Multimillion $ DOE DoD/DOT	1978 1980	U.S. DOE J. J. Brogan
12.	Transmissions - Supporting Research and Technology[b]	Technology data base, traction contact tests, fatigue tests, direct drive tests	275K DOE/DOT	1979	NASA-Lewis J. C. Wood
13.	Advanced Materials for Alternative Fuel Capable Directly Fired Heat Engines (Conference)[b]	Ceramics, coatings, alloys, components for combustion zones (diesels and turbines)	Multimillion $ International/ DOE	1979	DOE U.S. Industry International

(a) indicates more applicable to transportation tribology.
(b) indicates applicable to both transportation and industrial tribology.

mentioned previously in basic wear mechanisms, lubricants, and materials, only an estimated 25% are being actively pursued. Greater levels of funding are needed if tribology is to make the kind of energy conservation contribution that has been discussed here in any reasonable time frame. Because the benefits from any given tribological development will most likely be spread across many technologies and in more than one sector, a private firm would have great difficulty deriving full profits from these benefits. Thus, private research efforts may shun socially cost-effective research projects. Such projects are appropriate areas for government research support.

6.0 SUMMARY AND CONCLUSIONS

A socially optimal energy conservation strategy depends on both technical and market considerations. Technical considerations define the upper limit to the technologically feasible level of conservation. Market considerations determine how much of this upper limit is cost effective to actually achieve. When R&D on energy conservation technologies produces monetary benefits that can be fully achieved in the near term, private firms will decide which technologies are cost-effective to pursue. However, when R&D is inappropriate for the private sector to pursue because of insufficient patent protection, excessive risk, or other reasons, the federal government must assess the social cost-effectiveness of the various technology options. By concentrating on technologies that are not likely to be addressed by the private sector and by comparing the costs with the research benefits, the federal government can formulate an energy conservation R&D program that appropriately supplements private research efforts.

In this study Pacific Northwest Laboratory primarily addressed the technical side of the problem of identifying energy conservation research opportunities for the federal government. By concentrating on the conservation potential in each of the three end-use sectors, and by identifying the technologies with which to achieve this conservation, this study broadly defined the technical potential for energy conservation. The technologies with the greatest potential for saving energy in buildings, transportation, and industry were identified and the areas in which R&D could promote use of these technologies were discussed.

This study also addressed the market considerations concerning the potential energy conservation technologies. In the screening process that was applied to all of the identified energy conservation technologies, the issue of justified federally supported research was one criterion for identification. To meet this criterion, a plausible case had to be made that private industry would not perform the needed research to develop the technology. Technologies that were not shown to meet this criterion were excluded from further analysis.

The result of the procedure followed in this study was that the bulk of the analysis was focused on assessing technologies that offer both significant energy savings and a potential role for federal research. The individual discussions of the energy conservation technologies that were selected through the screening process make up a specialized data book of information needed to define research priorities in a federally sponsored energy conservation research program. However, note that the selection of these technologies through the screening process is not an exact step. Many technologies had to be excluded because of lack of sufficient information. Upon closer examination, these technologies could prove to be fruitful research areas. Thus, while the focus technologies selected for detailed analysis in this study can be assumed to be potentially promising research areas, those technologies not selected cannot be assumed to have no promise. A valid set of conclusions from this study must be restricted to evaluating and comparing the selected technologies. Further analysis is required to resolve uncertainties concerning many of the technologies not selected.

Even if conclusions are restricted to the focus technologies, recommending research funding on the basis of this study's results must be done carefully. As discussed previously, once a research option has been shown technically to offer energy conservation potential and to be inappropriate for private research support, the federal government must still show cost effectiveness to justify funding. To show cost effectiveness, a comparison of the research benefits and costs must be made. Evaluating costs involves both estimating the length and level of funding that would be required to bring the technology to fruition and considering the appropriate mix of private and public funding. Evaluating benefits from research involves calculating the likely energy savings and also any other nonenergy benefits, such as increased productivity or materials savings. Quantifying these benefits requires estimating the technology's time to commercialization, the degree of market penetration and the time to maximum market penetration. These estimations would involve consideration of any nontechnical barriers to the technology, such as high first cost to consumer (e.g., retooling) or institutional constraints (e.g., building codes).

Although the focus technology discussions deal with market viability and nontechnical barriers, a rigorous assessment of these factors was beyond the scope of this study. Formal evaluation of these technologies would require a detailed cost-effectiveness analysis.

Without a detailed cost-effectiveness analysis, some general conclusions can still be drawn from the information developed in this study. Because these conclusions require some degree of subjective judgment, they are open to debate. The fact that other interpretations or analyses based on the data in this study could arrive at slightly different results certainly does not undermine the study's usefulness. This study will have served its purpose if it provides a framework for a discussion of energy conservation research opportunities.

6.1 SUMMARY

The key points of this research are synthesized and condensed into a brief summary in Table 6.1. This table highlights the major information concerning the application, potential energy savings, research opportunities, existing research programs, and nontechnical barriers for the 30 focus technologies examined in Chapters 3, 4, and 5.

The first three columns in Table 6.1 identify the end-use sector and present the service or energy-using device and the energy conservation technology for each of the 30 technologies. To be concise many of the energy conservation technologies are defined at a fairly general level and actually represent groups of technologies. Additional detail on the individual technologies within each of these groups can be found in Chapters 3, 4, and 5.

The fourth column presents each technology's energy conservation potential, calculated in the previous chapters. The assumptions used in these calculations are given in the individual discussions of the focus technologies. To be consistent with the scenarios that were developed for estimating future energy savings, the energy conservation potential numbers are for the year 2010. Generally, these estimates are for those energy savings that depend on research to some degree. Many of the technologies could produce some energy savings without research support, however. For example, as discussed in Chapter 5, maximum use of heat exchangers could save over 15 quads per year, of which only about 1.5 to 3.0 quads per year depend on R&D. Also, because all estimates of conservation potential assume full market penetration of the technology, the energy savings estimates are not additive. For example, two alternate automotive engines clearly cannot capture the entire automobile market, although the maximum energy savings from each is calculated as if they could.

TABLE 6.1. Key Information About Selected Energy Conservation Technologies

Energy End-Use Sector: Buildings

Present Service or Device	Energy Conservation Technology	Estimated Maximum Energy Savings Quad/Year in 2010	Example Research Opportunities	Example Technical Barriers	Dependency of Energy Savings on R&D	Applications of R&D to Other End-Use Sectors	Representative Existing Research Programs	Nontechnical Barriers to Technology
Space Conditioning	Advanced Furnace/ Heat Pump Systems	1-2	- component development - refrigerant development - gas-fired heat pumps - novel heat pumps (Ericsson, Stiring,...)	- more efficient compressors, low cost, low T heat exchangers evaporative coolers - two fluid combinations, nonozone reactive fluids uniquely suited to temperature range - higher operating efficiency - proof of concept, less complex systems	High	Industry--some heat pump developments may be useful in waste heat recovery, although different temperature ranges require different equipment	Electric Power Research Institute Gas Research Institute	- high first cost to consumer
Space Heating	Alternate Fuels Combustion	Fuel switching could replace all fuel used for space heating	- health and environmental effects - corrosion control	- lower particulate emissions, control indoor air quality - minimize creosote build-up, prevent acid precipitation	Low	Industry--alternate fuels combustion for process heat and steam	Very little private research	- resource availability variations (biomass) - collection hazards (woodcutting)
Space Conditioning	Advanced Thermal Storage Materials	0.2-0.4	- improved thermal capacity - latent heat materials - thermal diodes	- new materials with higher heat capacity and conductivity - phase separation, supercooling - heat transfer mechanisms, material requirements	Low	Industry--thermal storage for load leveling	International Energy Agency Commission of European Industries Some private research	- aesthetic concerns over building design - building practices - building codes
Lighting	Advanced Lighting Concepts	0.1-0.3	- solid-state ballasts - advanced lamps (high-frequency flourescent and electrodeless, reflective coatings) - controls (task and daylighting) - human factors	- reliability, radiofrequency interference - proof of concept - problems with user interface - problems with user interface	Medium		Illuminating Engineers Society Lawrence Berkeley Lab--U.S. DOE	- aesthetic concerns over quality of light - health impacts of some lamps
Appliances	Integrated Appliances	0.5-1.5	- low-cost heat exchangers - sensors and controls - completely automated total energy system	- greater effectiveness - user interface - highly reliable controls	Low		Arthur D. Little	- high first cost to consumer - building practices - building codes

TABLE 6.1. (contd)

Energy End-Use Sector: Transportation

Present Service or Device	Energy Conservation Technology	Estimated Maximum Energy Savings Quad/Year in 2010	Example Research Opportunities	Example Technical Barriers	Dependency of Energy Savings on R&D	Applications of R&D to Other End-Use Sectors	Representative Existing Research Programs	Nontechnical Barriers to Technology
Automobiles	Direct Injection Stratefied Charge Engine	1.5-4.2	- fuel injection systems - basic combustion research	- optimize spray distribution - emissions control	Medium	Industry--basic combustion research applicable to industrial burners	Ford Texaco Mitsubishi	- health impacts of particulate emissions
Automobiles	Improved Diesels	1.5-4.3	- DI fuel injection systems	- high-speed capability - emissions control (particulates) - health effects of emissions	Medium		BNW British Leyland Chrysler Cummins Daimler-Benz Fiat Peugot Ford General Motors Isuzu Nissan Toyo Kogyo Toyota Volkswagen	- performance--acceptability - smoke, odor - health impacts of particulate emissions
Trucks	Adiabatic Diesel	0.6-1.7	- ceramic components	- high operating temperature - friction reduction (high temperature lubricants) - emissions control	High	Industry--adiabatic industrial engines, topping cycles	Cummins--U.S. Army	- high cost
Automobiles and Trucks	Stirling Engine	2.7-7.7	- heater head - piston rod seals - control system - component optimization (fuel economy)	- isothermalization, hydrogen permeation - work fluid leaks - faster response - combustion control, optimize engine/ power train combination combination	High	Industry--cogeneration, heat pumps	Mechanical Technology, Inc. United Stirling of Sweden American Motors Ricardo Ford General Motors NASA Lewis Shaker Research Co.	- high cost - materials availability
Automobiles and Trucks	Brayton Engine	2.2-6.4	- ceramic components - combustor - component design	- high operating temperature - emissions, combustion efficiency - aerodyamics of rotating components	High	Industry-cogeneration, heat pumps	Ford Chrysler General Motors Volvo Volkswagen Nissan Toyota Garret/Mack/KHD Carborundum Corning AiResearch Casting NGK Pure Carbon Co.	
Automobiles	Improved Otto Cycle Engine	1.25-3.6	- turbochargers - superchargers - constant-speed accessories - power train management	- variable geometry - variable geometry - mechanical development - reliable controls	Low		Garrett Corp. U. of Calif. U. of Mich SAI Ford Exxon	- inability of EPA mileage tests to assess benefits of improvements (e.g., constant speed accessory) - repair and maintenance

TABLE 6.1. (contd)

Energy End-Use Sector: Transportation

Present Service or Device	Energy Conservation Technology	Estimated Maximum Energy Savings Quad/Year in 2010	Example Research Opportunities	Example Technical Barriers	Dependency of Energy Savings on R&D	Applications of R&D to Other End-Use Sectors	Representative Existing Research Programs	Nontechnical Barriers to Technology
Automobiles	Advanced Conventional Transmission	1.0-2.9	- conventional transmission - variable volume oil pump - torque converter lockup - wide ratio four-speed gear set	- reoptimization - mechanical development - mechanical development - mechanical development	Low		Auto Manufacturers	- reduced acceleration and smoothness of shifting (public acceptance)
Automobiles	Continuously Variable Transmission	0.75-2.15	- rolling contact at high normal loads	- lubricants with high traction coefficients - wear resistant bearings - traction drive materials	High	Industrial--applications of CVT to industrial machinery	Chrysler General Motors Ford Sunstrand Corp. Toyota Vadetec Corp. Garrett Corp. Universities (relevant basic research)	- uncertain maintenance requirements - public acceptance
Automobiles	Reduced Engine and Drivetrain Friction	0.4-1.1	- modeling - piston rings - improved lubricants - lubricant additives	- analytic model of ring lubrication - piston ring optimization, new materials and coatings - low viscosity - boundary lubrications	Medium	Industry--basic tribology research, lubricants, and materials are applicable to industrial engines and machinery	Automakers Universites (basic research)	- public acceptance of low viscosity lubricants
Automobiles and Trucks	Decreased Rolling Resistance	0.09-0.25	- improved tire modeling - advanced rubber compounds - hard tire/advanced suspension systems	- accuracy - wear, traction, crack resistance - proof of concept	Medium		U.S. Department of Transportation Some private research (empirical)	- lack of awareness about tire maintenance and air pressure
Automobiles and Trucks	Vehicle Weight Recuction	0.9-2.6	- optimize existing materials - new materials--HSLA steel, Al alloys, plastics, composites, magnesium	- durability, reduced friction - forming, fabrication, durability, reliability	Medium		Automakers Materials Suppliers (large private research efforts)	- retooling costs involved in materials changes
Automobiles and Trucks	Alternate Fuels Combustion	Fuel switching could replace all petroleum used in autos and trucks	- coal/shale synfuels - alcohols - hydrogen - exotic fuels (powdered, coal/wood, slurries)	- combustion characteristics, emissions, engine compatibility - cold start, wear, emissions problems - feasibility study, permeation - combustion characteristics, emissions	Medium	Industry--characterization of combustion and emissions aspects of fuels would be applicable to industrial combustion. Buildings--slurries and powdered fuels might be used for space heating	Southwest Research Institute Gulf Research Ricardo Exxon General Motors International Harvestor, U.S. Army Billings Energy Research Suntech, Inc. Universities	- uncertain future cost and availability of petroleum - distribution difficulties in a multi-fuel system

TABLE 6.1. (contd)

Energy End-Use Sector: Industry

Present Service or Device	Energy Conservation Technology	Estimated Maximum Energy Savings Quad/Year in 2010	Example Research Opportunities	Example Technical Barriers	Dependency of Energy Savings on R&D	Applications of R&D to Other End-Use Sectors	Representative Existing Research Programs	Nontechnical Barriers to Technology
Process Heat, Steam	Improved Heat Exchangers	1.5-3.0	- improved heat exchangers - enhanced surfaces - high-temperatures heat exchanger - fluidized bed heat exchanger - plastic heat exchangers - direct contact heat exchangers	- fouling, corrosion, fluid-induced vibration - greater heat-transfer coefficient - high-temperature materials - determining heat-transfer coefficients - materials development - fluid miscibility	High	Buildings--waste heat recovery, district heating and cogeneration systems Transportation--some heat exchanger research could be utilized in advanced heat engines	Idaho Falls Nat. Lab, U.S. DOE Heat Transfer Research Institute Hague International Dupont EPRI Harwell General Atomic AiResearch Jet Propulsion Lab. Argonne Nat. Lab Many Others (specialized applications)	- cost
Process Heat, Steam	Industrial Heat Pumps	1-3	- Rankine cycle working fluids - heat exchangers - Stirling cycle - absorption cycle - Ericsson-Ericsson	- high-temperature fluids - greater heat-transfer coefficient - greater cycle efficiency - high-temperature fluid pairs - greater cycle efficiency	Medium	Buildings--some heat pump developments may be applicable to space conditioning, although industrial applications tend to be higher temperature and require different equipment	Oak Ridge Nat. Lab. Battelle-Columbus Westinghouse Institute of Gas Tech. Gas Research Institute Carrier Corp. General Electric Monsanto Thermo Electron Sunstrand Nat. Highway Safety Council	- unfamilarity in many industrial applications - cost
Electricity/Process Heat & Steam	Cogeneration Technologies	2-3	- fluidized bed combustion - alternative fuels combustion - component compatibility - high-temperature gas turbine - high-temperature air preheaters - fuel gas cleanup systems and coal gasifiers - working fluids for bottoming cycles	- higher temperature capability - emissions - erosion - high-temperature materials - reliability - tars and particulate emissions - high-temperature fluids	Low	Buildings--total energy systems (cogeneration) for buildings	Westinghouse General Electric Thermo Electron Carrier Sunstrand MTI Garrett AiResearch	- capital costs - uncertainty with new role for industry
Process Control	Systems Controls and Sensors	0.8-8	- smarter sensors - instrument performance - flame quality sensors - fuel analysis sensors - stack gas measurement - harsh environment sensors - systems methodology and modeling	- new physical sensing principles - accuracy, speed of response - accuracy - accuracy - durability in erosive environments - durable materials - optimizing complex systems	Medium	Transportation--microprocessor control of engine, transmission and auxiliaries Buildings-control of space contiion-ing, lighting and integrated appliances	National Burearu of Standards Much private research into microprocessors	
Materials	Scrap Recycle	2.5-3.5	- processing aluminum alloy steel titanium copper tires plastics	- detection, classification, separation methods eliminate impurities separate alloys remelt chemical reduction size reduction separation	Medium		EPA Bureau of Mines Dept. of Agriculture American Society for Testing Materials	- uncertain future attitudes and actions concerning recycling (presents risk to firms marketing equipment)

TABLE 6.1. (contd)

Energy End-Use Sector: Industry

Present Service or Device	Energy Conservation Technology	Estimated Maximum Energy Savings Quad/Year in 2010	Example Research Opportunities	Example Technical Barriers	Dependency of Energy Savings on R&D	Applications of R&D to Other End-Use Sectors	Representative Existing Research Programs	Nontechnical Barriers to Technology
Process Heat and Steam	Industrial Insulation	0.25-0.5	- hot wall refractories - basic data on properties - rigid insulation for steam systems	- durability under high temperature conditions long-term performance - better mechanical properties and lower thermal conductivity	Low	Buildings--basic research may be useful in buildings insulation, although applications differ greatly	American Society for Testing Materials National Bureau of Standards	- cost
Distillation	Critical Fluid Extraction	0.6-1.0	- improved solvents - additional applications	- improved distribution coefficient, solvent selectivity - identification	High		Arthur D. Little, Inc. National Bureau of Standards	
Concentration of Black Liquor (Pulp Industry)	Freeze Crystallization	0.1	- process techniques	- nontriple point freezing to minimize losses of volatile gases	High	Industry--food concentration (acetic acid, orange juice, milk)	Concentration Specialists, Inc.	
Chemical Reactions (Chemical Industry)	Catalysts	0.18-0.95	- study of surface science	- fundamentals of catalyst mechanisms, selectivity	High	Industry--petroleum industry chemical reactions. Emissions control Transportation--emissions control, fuel catalysts	All major chemical and petroleum industries	- proprietary information
Water Removal	Improved Drying Technologies	0.4-0.6	- vapor compression - heat pump drying - centrifugal fluidized bed drying - microwave freeze drying	- higher efficiency - higher efficiency - fluidization characteristics of bed materials - "microwave breakdown" (ionization)	Medium		Agricultural Universities (U.C. Davis, Cal. Poly, San Luis Obispo, Michigan State, U. of Minn.) Dept. of Energy	- lack of information available in industry
Mechanical Drive/ Industrial Engines	Alternate Fuels Combustion	Fuel switching could replace all fuels used in industrial engines	- emissions - materials compatility - slurries - component compatability	- NO_x emissions control - corrosion resistant materials - atomization, injection, particle-liquid interaction optimization, radiation loss and control - slag formation from low-Btu gas in turbine	Medium	Transportation--much research would apply to use of alternate fuels in vehicle engines	Southwest Research Institute	- slow (20 yr) turnover of industrial engines
Energy Conversion, Chemicals Production, Separation Processes	Genetic Engineering	Fuel switching to biomass could replace most natural gas used in industry Fuel switching to biomass could replace some petroleum used in organic chemicals production	general assessment of: - separation and material recovery applications - energy conversion of biomass to hydrogen, methane, or ethanol - chemical feedstock processing	- identification of genetic systems and vectors - immobilization of cells	High	Transportation--fuels produced through genetic engineering could be used in vehicle engines	Pharmaceutical Research: Bethesda Research Labs Biogen Cetus Genetech Genex Molecular Genetics New England Biolabs	- human health and environmental concerns - philosophical dilemma
Industrial Engines/ Mechanical Drive	Tribology	1.2-1.3	- rolling contact - sliding (abrasive) wear - lubricants - nonlubricated materials - seals and bearings	- elastohydrodynamic lubrication technology, viscous properties - wear particle generation - high-temperature capability - high-temperature, durable materials - high-temperature, durable materials	High	Transportation--much of the fundamental work in tribology would apply to friction and wear reduction in vehicle engines. Also, adiabatic diesel and CVT would benefit from research	Pacific Northwest Laboratory NASA Lewis Jet Propulsion Lab. Universities National Center for Tribology, Risely, England	- lack of awareness of tribology technology

The fourth and fifth columns of Table 6.1 summarize research opportunities and technical barriers relating to each of the 30 energy conservation technologies. In many cases, these research opportunities and technical barriers actually summarize more specific activities that are given in further detail in the individual discussions of the focus technologies. As previously mentioned, both the research opportunities and technical barriers identified in this study are intended to be examples only. Closer examination of each focus technology will undoubtably reveal additional activities. Proposing specific activities needed to bring particular technologies to fruition is the responsibility of the technical research community. A systems analysis overview such as this should not be substituted for judgment of the technology experts at the level of research task definition.

The sixth column in the table represents the study team's subjective judgment of the degree to which the energy savings in Column 4 depend on the research in Column 5. These ratings are the result of the study team's general assessment of the various technical and market factors relating to each technology. A rating of "High" means that virtually all of the energy savings hinge on R&D. "Medium" signifies that over half of the energy savings require research to be achieved. "Low" indicates that the majority of energy savings from the energy conservation technology could be obtained without R&D.

The seventh column identifies other applications of the research in Column 5. These additional applications can be very important factors in determining the overall cost effectiveness of various types of research. For this study, these multisector applications are simply identified as important to the focus technologies. Further work is needed to evaluate their energy conservation potential and specialized research opportunities.

The eighth column of the table presents a brief overview of organizations that are conducting research relevant to each focus technology. These summaries are not complete, as organizations may be omitted and also research budget size is not included. A large but crucial future task is to catalog the existing public and private research programs that relate to energy conservation. When combined with an assessment of the potential applications of energy conservation technologies, such as this study, a catalog of existing research would enable the federal government to identify research gaps and target support to fill these gaps.

The last column of Table 6.1 summarizes some of the major nontechnical barriers to each technology. In many cases, these nontechnical barriers could prove to be technical. For example, improved technology might lower the first cost, or improve consumer acceptance of a device. These items are listed as nontechnical barriers because they could become factors that limit the use of a technology after it is technically developed. Because these nontechnical barriers could be major impediments to a technology, they should be given early consideration from either a technical or nontechnical perspective when evaluating technologies for research support.

6.2 CONCLUSIONS

Looking at Table 6.1 from a general perspective reveals some broad conclusions concerning the three energy end-use sectors. In buildings only 5 technologies were selected as meeting the screening criteria and of these most were rated as having a low degree of dependency on research. In transportation, 12 technologies were selected, many of which were rated as having a high dependency on research. At the same time, the transportation technologies have by far the largest number of supporting private research programs. In industry, 13 generic technologies were selected, several of which were rated as having a high dependency on research. Although many of the industrial technologies are supported by several research programs, these research programs are often directed at fairly specific applications of the technologies, rather than generic development of the technological concept.

Table 6.2 summarizes some general comparisons among the buildings, transportation, and industry energy end-use sectors. All three sectors are considered to have high energy conservation potential. Numerous studies in recent years have shown that U.S. energy use could be well below current levels without causing a decline in the standard of living.[a] However, because of differences among the three sectors, R&D would have varying amounts of influence on the degree of energy conservation in each sector.

(a) Wolfe 1975; Council on Environmental Quality 1979; Lovins 1976; National Academy of Sciences 1980; Ross and Williams 1981; Stobaugh and Yergin 1979.

TABLE 6.2. Comparisons of the Three Energy End-Use Sectors

	Buildings	Transportation	Industry
Energy Conservation Potential	High	High	High
Technical Sophistication of Current Energy Use	Low	High	Medium
Number of Energy End Uses	Low	Low	High
Private Research Capabilties	Low	High	Medium
Need for Research to Realize Energy Conservation Potential	Low	Medium	High

As shown in Table 6.2, energy use in the buildings sector is fairly unsophisticated and concentrated in a few major end uses (e.g., space conditioning, water heating, and lighting). Transportation energy-using equipment is much more technically sophisticated than buildings equipment. Traditionally, low energy prices have not provided sufficient incentives to apply this technical sophistication to increasing energy efficiency. Higher energy prices, however, have already begun to spawn energy-efficient transportation equipment. Like buildings, transportation is dominated by a few energy end uses, primarily autos, trucks, and aircraft.

Industry, on the other hand, contains many specific energy end uses, many of which have very specialized requirements. This characteristic necessitated a far more lengthy treatment of industry than was required of buildings and transportation. Discussions of individual industries were necessary to address the specific end-use requirements found in the industrial sector. In terms of technical sophistication, industry as a whole probably lies somewhere between buildings and transportation. A wide variation in sophistication is clearly present among individual industries.

Research capabilities in the three end-use sectors vary significantly. The buildings sector has the least research capabilities, largely because of the fragmented nature of the construction industry and building equipment vendors. Limited research capabilities are appropriate because of the low technology intensiveness and small number of energy uses in buildings. The majority of the energy conservation that may be achieved in buildings can probably be accomplished with very little R&D support.

Research capabilities in the transportation sector are very significant because of the auto industry's oligopolistic structure. Aerospace research capabilities are also very substantial. Therefore, while energy conservation in the transportation sector will require research support, private industry has much of the technical skill. Federally supported research could foster cooperation between and among private industry and other research organizations on advanced concepts. However, major portions of the transportation sector are not in dire need of federal research support to achieve their energy conservation potential.

The industrial sector has widely varying research capabilities. Overall, industry has greater research capabilities than buildings, but less than transportation. In cases where industrial research capabilities are limited, the private sector may be unable to pursue long-range, high-risk research that could result in very significant energy savings. Development of advanced industrial processes could also improve the competitive position of domestic industries on the world market. An improved position in the world market would be particularly important to the economically ailing domestic basic materials industries. From this cursory overview, the industrial sector appears to offer the largest number of promising research opportunities for federal support.

The information in Table 6.1 can be used to go beyond simple comparisons among energy end-use sectors and can provide an indication of the types of technologies that are potentially promising for federal research support. Table 6.3 summarizes the research opportunities that the study team judged to be of most interest to the federal government. Because a detailed cost-effectiveness analysis was not done on these ideas, no formal ranking or comparison is attempted. Rather, they are simply listed as promising areas, considering the analysis performed in this study.

In buildings, research into advanced heat pump technology appears promising even though large energy savings are possible with existing heat pumps. The energy use in buildings space heating is so large that even small efficiency improvements result in significant energy savings. Research into lighting technology offers promise in commercial buildings, although the energy

TABLE 6.3. Promising Energy Conservation Research Opportunities

Buildings

- development of advanced heat pump concepts (Stirling, Ericsson, gas-fired, working fluids)
- research into advanced lighting technologies
- control of health and environmental impacts of alternative fuels combustion

Transportation

- ceramic components for heat engines
- fundamental tribology (sliding and rolling wear, high temp. lubrication)
- fundamental combustion research
- modeling of tires
- fundamental development of lightweight materials
- characterization of alternative vehicle fuels

Generic Industrial Technologies

- studies of heat exchanger operation and materials
- development of advanced industrial heat pumps (Stirling, Ericsson-Ericsson, absorption, working fluids)
- development of advanced sensors and control methodologies
- study of methods of scrap materials separation
- fundamental studies of industrial insulation (durability, high temp. performance)
- development of improved distillation and water removal processes (critical fluid processes, membranes, freeze crystallization, drying processes)
- characterization of alternative industrial fuels
- studies of basic mechanisms of catalysts and chemical processes
- investigation of applications of genetic engineering to energy and chemicals conversion
- fundamental tribology (friction, wear, lubricants, materials)

Advanced Basic Materials Processes

- ore-to-powder steelmaking
- direct one-step steelmaking
- powder metallurgy
- thermal reduction of bauxite to Al-Si alloy
- submerged combustion glassmaking
- food sterilization processes

conservation payoffs may be larger from research into human factors and improved controls than research into advanced bulbs. Research into the important environmental and health aspects of alternate fuels combustion in buildings warrants attention because private firms are not likely to perform this research, since the benefits are in the form of improved health and environmental quality, rather than profits.

In transportation the federal government must establish a research program that does not interfere with the sizeable private research organizations. In general, private manufacturers are better equipped to select and develop engine and vehicle designs. The government should restrict its activities to areas that build up a technological information base to aid the manufacturers in their R&D efforts. Research into ceramic heat engine components, fundamental tribology, combustion processes, tire modeling, lightweight materials, and characteristics of alternate fuels would provide useful information to the automakers without constraining their technological options. The private manufacturers would then be able to use the results from federally supported research in these areas in the manner they deem most promising.

In industry the federal government could support energy conservation in two ways. First, the government could develop technologies that are generic to more than one industry and therefore have more benefits when viewed from an industry-wide perspective than from a single industry. Industry research programs are not likely to adequately address these technologies because they generally realize only a part of the benefits from developing them. Second, the government could perform long-range, high-risk research into advanced basic materials processes that would not only save energy but would improve the economic viability of the basic materials industries as well.

Research into generic industrial energy conservation technology that appears to offer promise includes advanced heat exchangers, advanced industrial heat pumps, sensors and control methodologies, methods of scrap materials separation, industrial insulation, improved distillation and water removal processes, characteristics of potential alternate industrial fuels, basic mechanisms of catalysts and chemical processes, energy conservation applications of genetic engineering, and fundamental tribology. As discussed in Chapter 5, these technologies are those most likely to play a significant role in saving energy across most industries.

This study did not propose to compile a list of innovative basic materials processes. However, in the course of reviewing energy conservation options in specific industries, some processes were uncovered. Examples of high-risk, advanced basic materials processes that were identified in this study are ore-to-powder systems, direct one-step steelmaking, and powder metallurgy in the steel industry, thermal reduction of bauxite to Al-Si Alloy in the aluminum industry, and submerged combustion glassmaking, and food sterilizaton processes in the food processing industry. More work is needed in this area to generate and evaluate a list of options for long-range research into advanced basic materials processes.

In summary, this study provides a thorough, systematic approach to identifying energy conservation research opportunities from an end-use perspective. By screening the energy conservation technologies that were identified according to their conservation potential and need for research, the analysis of this study was concentrated in the areas offering the most promise as research opportunities. A large body of consistent information was developed in conjunction with each of the selected technologies. However, this study is more than a simple data book of useful facts and figures about energy conservation technologies. By addressing the issue of the appropriate role for federal support of energy conservation research relating to the selected technologies, this study makes the first step toward identifying the components of a federal energy conservation research program. The next step needed is to build on this analysis by developing further information about technologies where lack of data prevented their evaluation in this study and by performing a formal cost-effectiveness analysis of the promising energy conservation technologies to assess their relative merit. These steps will enable the federal government to play an optimal role in developing the all-important energy option of conservation.

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