A Preliminary Overview of Innovative Industrial Materials Processes

**G. J. Hane
S. G. Hauser
D. E. Blahnik
D. E. Eakin**

**W. E. Gurwell
T. A. Williams
R. Abarcar
J. Szekely
W. B. Ashton**

September 1983

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

**Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute**

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

NTIS Price Codes
Microfiche A01

Printed Copy

Pages	Price Codes
001-025	A02
026-050	A03
051-075	A04
076-100	A05
101-125	A06
126-150	A07
151-175	A08
176-200	A09
201-225	A010
226-250	A011
251-275	A012
276-300	A013

A PRELIMINARY OVERVIEW OF
INNOVATIVE INDUSTRIAL
MATERIALS PROCESSES

G. J. Hane	W. E. Gurwell
S. G. Hauser	T. A. Williams
D. E. Blahnik	R. Abarcar(a)
D. E. Eakin	J. Szekely(b)
	W. B. Ashton

September 1983

Prepared for
Energy Conversion and Utilization
Technologies Division
Office of Energy Systems Research
Conservation and Renewable Energy
U. S. Department of Energy
under Contract DE-AC06-76RL0 1830

Pacific Northwest Laboratory
Richland, Washington 99352

(a) Energetics, Inc., Columbia, Maryland.

(b) Massachusetts Institute of Technology, Cambridge, Massachusetts.

PREFACE

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 the following:

Abarcar, R. and D. Johnson. 1983. ECUT Data Reference Series: Lightweight Materials for Ground Transportation. Pacific Northwest Laboratory, Richland, Washington.

Abarcar, R. and D. Johnson. 1983. ECUT Data Reference Series: Materials for Advanced Heat Engines. Pacific Northwest Laboratory, Richland, Washington.

Chockie, A. et. al. 1983. An Evaluation of Stationary Combustion Research Needs. Pacific Northwest Laboratory, Richland, Washington.

Chockie, A. and D. Johnson. 1983. ECUT Data Reference Series: Stationary Combustion Systems. Pacific Northwest Laboratory, Richland, Washington.

Hane, G. and D. Johnson. 1983. ECUT Data Reference Series: Otto Cycle Engines in Transportation. Pacific Northwest Laboratory, Richland, Washington.

Hane, G. 1983. Efficiency Evaluation of the DISC, DHC, and DI Diesel Engines. PNL-4568, Pacific Northwest Laboratory, Richland, Washington.

Hane, G. et. al. 1983. Energy Conservation Research and Development Needs: A Review and Synthesis of the Literature, Phase II. PNL-4571, Pacific Northwest Laboratory, Richland, Washington.

Hopp, W. et. al. 1982. 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.
- U.S. Department of Energy. 1983. Energy Conversion and Utilization Technologies Program Report, 1981-1982. U.S. Department of Energy, Washington, D.C.
- Young, J. and D. Johnson. 1983. ECUT Data Reference Series: Ammonia Synthesis. Pacific Northwest Laboratory, Richland, Washington.

W. B. Ashton
Project Manager

SUMMARY

Previous work in evaluating the potential for industrial energy conservation through research and development has focused almost exclusively on evolutionary improvements in current processes. Although significant energy conservation potential exists through continued evolutionary improvements, dramatic improvements will require highly innovative advances. One category of such advances involves alternative approaches to the conventional techniques of processing materials. The U.S. Department of Energy (DOE) contracted with Pacific Northwest Laboratory (PNL) to perform a review of such innovative industrial materials processes that have the potential for significant improvements in energy use, yet require long-term research to achieve that potential. The potential of revolutionary changes in the basic materials processing industries has been suggested by many recognized researchers including Gibbons and Chandler (1980), Chioggiogi (1979), Ross and Williams (1981), and Berg (1979), and by several committees including CONAES (1979) and the SERI panel (1981). Potential revolutionary alternatives for eight major materials processing industries are reviewed in this study. These industries are chemicals; iron and steel; aluminum; petroleum refining; paper and pulp; food and kindred products; stone, clay, and glass; and textiles.

Because of the pioneering nature of this study, the scope was limited to alternative processes that have been suggested by members of the research and industrial communities. The purpose of the effort was not to discover radically new methods by independently analyzing each industry, but rather to review the ideas that have already been formulated to determine the potential for change and for further major innovations.

The candidate processes identified in this effort ranged in development from laboratory tested to conceptual. Although potential energy savings were the focus of this study, other information was also sought to help define the processes. This information includes the process or processes displaced, samples of the major technical barriers that need to be overcome, and the level of current research.

In total, 45 candidate processes were identified. The chemical and the iron and steel industries presented the most well-developed candidates, whereas those processes identified in the pulp and paper and textiles industries were the most speculative. Examples of the candidate processes identified include direct steelmaking and ore-to-powder systems, which potentially require 30 to 40% less energy, respectively, than conventional steelmaking systems; membrane separations and freeze crystallization, which offer up to 90% reductions in energy use when compared with distillation; the cold processing of cement, which offers a 50% reduction in energy requirements; and the dry forming of paper, which offers a 25% reduction in the energy needed for papermaking.

A review of all the industries revealed that the revolutionary alternatives often use similar concepts in avoiding current process inefficiencies. These concepts include using chemical, physical, or biological processes to replace thermally intensive processes; using specific forms of energy to minimize wasteful thermal diffusion; using chemical, biological, or ultrasonic processes to replace physical reduction; combining multiple processing steps into a single reactor; using a dry processing to eliminate energy needed for evaporation; and using sterilization or biotechnology to reduce the need for refrigeration.

CONTENTS

SUMMARY	iii
1.0 INTRODUCTION	1.1
MEASURES OF INNOVATIVE PROCESSES	1.2
INDUSTRIAL ENERGY CONSERVATION POTENTIAL	1.3
INDUSTRIAL ENERGY CONSERVATION ACHIEVED	1.6
NEED FOR FURTHER RESEARCH	1.6
2.0 METHODOLOGY AND SCOPE	2.1
3.0 INNOVATIVE INDUSTRIAL MATERIALS PROCESSES	3.1
3.1 IRON AND STEEL	3.1
3.1.1 Alternative Industrial Materials Processes	3.7
3.1.2 Investigation of Selected Processes	3.15
3.2 ALUMINUM	3.17
3.2.1 Advanced Aluminum Processes	3.20
3.3 CHEMICALS	3.26
3.3.1 Alternative Industrial Materials Processes	3.27
3.4 PETROLEUM REFINING	3.39
3.4.1 Alternative Industrial Materials Processes	3.42
3.4.2 Investigation of Selected Processes	3.48
3.5 PULP AND PAPER	3.51
3.5.1 Alternative Industrial Materials Processes	3.60
3.5.2 Investigation of Selected Processes	3.68
3.6 FOOD AND KINDRED PRODUCTS	3.70
3.6.1 Alternative Industrial Materials Processes	3.72
3.7 STONE, CLAY AND GLASS	3.77
3.7.1 Alternative Industrial Materials Processes	3.80

3.8	TEXTILES	3.83
3.8.1	Alternative Industrial Materials Processes	3.84
3.9	GENERIC REVOLUTIONARY PROCESSES	3.88
4.0	SUMMARY AND CONCLUSIONS	4.1
	REFERENCES AND BIBLIOGRAPHY – GENERAL	R.1
	REFERENCES AND BIBLIOGRAPHY – IRON AND STEEL	R.3
	REFERENCES AND BIBLIOGRAPHY – ALUMINUM	R.4
	REFERENCES AND BIBLIOGRAPHY – CHEMICALS	R.5
	REFERENCES AND BIBLIOGRAPHY – PETROLEUM REFINING	R.9
	REFERENCES AND BIBLIOGRAPHY – PULP AND PAPER	R.11
	REFERENCES AND BIBLIOGRAPHY – FOOD AND KINDRED	R.15
	REFERENCES AND BIBLIOGRAPHY – GLASS, CEMENT AND CERAMICS	R.16
	REFERENCES AND BIBLIOGRAPHY – TEXTILES	R.18

FIGURES

1.1	Relationship Between Efficiency Improvement and Post-Embargo Capital Stock	1.7
1.2	Comparison of Selected Fuel Costs	1.9
3.1	Conventional Iron and Steelmaking Processing Sequence	3.2
3.2	Estimated U.S. Level-1 Energy Consumption by Major Process Units in 1976	3.4
3.3	Changes in Steelmaking Methods in the United States	3.5
3.4	Comparative Costs of Energy, Labor, and Capital in the Primary and Finishing Ends of Steelmaking	3.7
3.5	Direct Steelmaking	3.9
3.6	One Proposed Ore-to-Powder Steelmaking Process	3.10
3.7	Plasma Steelmaking	3.12
3.8	Cross Section of Hall-Héroult Aluminum Reduction Cell	3.19
3.9	Conventional Aluminum Production Process and Advanced Alternative Processes	3.21
3.10	Mitsui Carbothermic Aluminum Production Process	3.23
3.11	Trichloride Electrolysis Cell	3.24
3.12	Types of Membrane Separation Processes	3.37
3.13	Conventional Petroleum Processing Sequence and the Use of Membrane Separation Processes	3.44
3.14	Pulp, Paper and Paperboard Industry Changing Fuel Mix, 1972-1981	3.53
3.15	U.S. Paper Industry	3.54
3.16	Pulp, Paper and Paperboard Industry Cost of Purchased Fuels and Electric Energy as a Percentage of Value of Shipments, 1972-1981	3.55
3.17	Conventional Pulp and Paper Processing Sequence	3.58
3.18	Dry Forming	3.65

3.19	Modified High Fructose Corn Syrup Process	3.73
3.20	Generalized Process Flow Diagram for Glass Production	3.78
3.21	Cold Processing in the Generalized Process Flow for Cement Production	3.78
3.22	Conventional Textile Processing Sequence and the Alternative Spray Forming Process	3.87

TABLES

1.1	Comparison of Specific Fuel Consumption of Known Processes with Theoretical Minimum for Selected U.S. Industries . . .	1.4
1.2	Estimated Technological Limits to Industrial Energy Conservation	1.5
1.3	Summary of Status of Industrial Energy Conservation . . .	1.7
1.4	Industrial R&D Expenditures in 1981	1.10
3.1	Aluminum Industry Energy Consumption in 1980	3.17
3.2	Smelter Energy Consumption in 1980	3.18
3.3	30 Top Energy-Consuming Products in 1977	3.28
3.4	Potential Bioproducted Chemicals	3.31
3.5	Separation Operations	3.35
3.6	Energy Use by Petroleum Refining Process	3.40
3.7	U.S. Refining Capacity by Plant Size in January, 1980 . . .	3.41
3.8	Comparative Energy Use for Desalinating Sea Water	3.49
3.9	U.S. Pulp, Paper and Paperboard Industry Estimated Fuel and Energy Use in 1981	3.52
3.10	Major Energy-Consuming Processes in Papermaking	3.56
3.11	Pulp and Paper Industry R&D Needs and Opportunities Identified in Literature	3.61
3.12	Energy Consumption in the Food and Kindred Products Industry .	3.70
3.13	Example Generic Materials Processing Alternatives	3.89
4.1	Summary Table of Advanced Industrial Materials Processes . .	4.2
4.2	Generic Categories of the Revolutionary Processes	4.14

1.0 INTRODUCTION

The purpose of this study was to perform a preliminary identification of innovative industrial materials processes that have the potential for significant energy conservation yet require long-term research to achieve that potential. This study is therefore intended as a preliminary survey of the breadth of potential long-term, revolutionary energy-conserving processes that have been suggested in eight major materials processing industries: chemicals; iron and steel; aluminum; petroleum refining; pulp and paper; food and kindred products; stone, clay, and glass; and textiles.

The broad list of energy conservation measures can be divided among three basic categories: 1) housekeeping, 2) retrofit and evolutionary change, and 3) major, potentially revolutionary, process changes. Housekeeping measures are the simplest and least costly to implement. Typical examples include lowering thermostats and adjusting air/fuel ratio controls in boilers and furnaces. The second category of measures involves some equipment modification or replacement to increase the efficiency of energy use. The measures involve some capital expense and are normally performed after the housekeeping improvements have been exploited. In this case, although the equipment is upgraded through evolutionary measures, the basic sequence of materials processing remains largely the same. Examples of evolutionary improvements include waste heat recovery, cogeneration, and the use of automatic controls. The third category involves major changes in some of the basic materials processes.

Unlike the first two categories, the large potential for energy conservation through revolutionary materials processes has received little attention. The potential for dramatic efficiency improvements has been suggested by several notable researchers, including Gibbons and Chandler (1980), Chiogiogi (1979), Ross and Williams (1981), and Berg (1979) and was pointed out in the CONAES Study (1979) and the SERI Study (1981). However, information describing the specific processes that would exploit this potential has yet to be gathered. A review of studies addressing research and development needs directed toward energy conservation revealed that near-term retrofit and evolutionary improvements in many of the materials processing industries appeared to be well addressed (Hopp et al. 1982). However, a clear gap existed in studies

that addressed long-term processing alternatives. The only industry in which a significant amount of pioneering work has been performed in this area appears to be in iron and steel. This work has been closely tracked by one of this report's authors, J. Szekely. This study was therefore undertaken to explore these long-term possibilities.

MEASURES OF INNOVATIVE PROCESSES

The characteristics of a revolutionary process are difficult to define, and a commonly accepted definition does not seem to exist. Webster's definition, "bringing about a very great change," is too broad for the application intended here. Marc Ross^(a) has suggested that a characteristic that marks a revolutionary process is its ability to replace the current process before normal economic retirement. However, in projects still requiring long-term research, the economic characteristics of the final process are often difficult to determine.

In defining the term "revolutionary," a useful analogy can be drawn with Berg's definition of innovation. In defining innovation, Berg (1982) has proposed the notion of discontinuous conceptual change that eliminates irreducible costs associated with the conventional process. For example, the conventional method of curing can coatings has been to apply a liquid coating and then to process the cans through a furnace to evaporate the solvent. Using this process, the entire volume of the can needs to be heated, and the heating rate of the can is limited by the thermal diffusion properties of the can material. Regardless of how the furnace is redesigned, these two limiting irreducibles will be present, causing penalties in energy use as well as processing times. To avoid this problem, an alternative method has been developed that involves applying UV radiation to the surface to be cured. The UV strikes photoinitiators in the coating solvent, and these photoinitiators incite the liquid coating to polymerize and harden. This specific surface application of energy eliminates both the volumetric heating requirement and thermal diffusion time delay of the previous method. The innovative method thus avoided the irreducibles in the conventional process.

(a) Personal communication with Marc Ross, Alliance To Save Energy, 1982.

This notion may be usefully extended to define revolutionary processes. Revolutionary processes involve conceptual differences in the conventional methods that are not merely variations in the current technique. Therefore, a definition for a revolutionary process might be as follows: "an alternative that involves a discontinuous conceptional change in the current processing methods and avoids some irreducible aspect of the conventional process, resulting in a dramatic increase in efficiency."

Promising revolutionary processes most likely will result in an increase in the overall productivity of a process as measured by labor, capital, materials, as well as energy requirements. Although all of these production factors are important, this study is primarily concerned with processes that will substantially reduce the amount of energy needed without adversely affecting other costs.

Many of the major materials processing methods currently employed by the industry have been in use for decades, centuries, and even millennia. For example, the basic textile process dates back to the Swiss lake dwellers of neolithic times. The iron age dates back to approximately 1200 B.C., and the first blast furnaces used in North America were built in the mid-seventeenth century. The basic steps used in papermaking are largely unchanged since they were conceived in China in approximately 105 A.D. Regenerative glassmelting was invented by Siemens in 1856, and ammonia synthesis was invented by Harber and Bosch in 1913. Given the age of various materials processing methods, it is interesting to note that little apparent effort has been directed into developing alternative methods. However, the age of the process does not necessarily indicate poor efficiency.

INDUSTRIAL ENERGY CONSERVATION POTENTIAL

The effectiveness with which energy is used in the various materials processes can be evaluated by applying the first and second laws of thermodynamics in an availability analysis. The use of availability analysis to analyze the efficiency of specific processes or technologies has received much attention in recent years. However, availability analysis can also be used to gauge the potential efficiency improvement possible in converting the raw materials into

the finished product. In this report efficiency is defined as the ratio of the actual energy used to the total amount of energy supplied.

Gyftopoulos (1975) has calculated the theoretical minimum specific fuel consumption necessary in several materials processing industries: iron and steel, petroleum refining, pulp and paper, primary aluminum, and cement. The results of this analysis are shown in Table 1.1. The difference between the actual efficiencies and the theoretical minimum is an indication of the energy conservation potential.

DOE (1980) performed similar analysis to estimate available and theoretical efficiency improvements in several of the materials processing industries.

TABLE 1.1. Comparison of Specific Fuel Consumption of Known Processes with Theoretical Minimum for Selected U.S. Industries (Gyftopoulos 1975)

	1968 Specific Fuel Consumption (Btu/ton)	Potential Specific Fuel Consumption Using Technology Existing in 1973 (Btu/ton)	Theoretical Minimum Specific Fuel Consumption Based Upon Thermodynamic Availability Analysis (Btu/ton)
Iron and Steel	26.5×10^6	17.2×10^6	6.0×10^6
Petroleum Refining	4.4×10^6	3.3×10^6	0.4×10^6
Paper	39.0×10^6 (a)	23.8×10^6 (a)	Greater than -0.2×10^6 (b) Smaller than $+0.1 \times 10^6$
Primary Aluminum Production(c)	190×10^6	152×10^6	25.2×10^6
Cement	7.9×10^6	4.7×10^6	0.8×10^6

(a) Includes 14.5×10^6 Btu/ton of paper produced from waste products consumed as fuel by paper industry.

(b) Negative value means that no fuel is required.

(c) Does not include effect of scrap recycling.

These estimates are shown in Table 1.2. The theoretical improvements are again seen to be substantial. The table shows that pulp and paper have a second law minimum of zero energy use. In other words, the raw material theoretically can be converted to the product without using external energy because the embodied energy of the product is less than that of the feedstock. In practice the processes do require a significant amount of energy for steps such as feed preparation (cutting, debarking, chipping, etc.).

The estimates of improvements from best available technology shown in Table 1.2 apply to the conventional materials processing sequences. These estimates indicate the conservation potential that may be achieved through evolutionary technology improvements. In general, a 20 to 35% savings of energy across the industries are possible through evolutionary changes.

On the process-specific level, the first and second laws of thermodynamics are also often used to assist in identifying areas of potential improvement. Availability analysis is again used to evaluate the efficiency of providing the service. However, when used at this level, availability analysis is not always a good indicator of the realistic potential for revolutionary process improvements. For example, the basic oxygen furnace used in steelmaking has a second law efficiency in the range of 85 to 90% (Derouette 1979). This would indicate that very little improvement might be expected. Although little

TABLE 1.2. Estimated Technological Limits to Industrial Energy Conservation (DOE 1980)

<u>Industry</u>	<u>Industry Estimates of Best Available Technology Improvement (%)</u>	<u>Estimates of Theoretical Limits of Energy Efficiency Improvement (%)</u>
Steel	30 - 35	62 - 82
Petroleum Refining	10 - 15	90
Paper	30 - 40	100
Aluminum	15 - 25	88
Cement	20 - 30	93
Olefins	20 - 30	59
Textiles	25 - 30	95

improvement can be achieved if this process step continues to be used, efficiency gains can still be achieved by eliminating the requirement for this furnace via the direct steelmaking route. In this overall efficiency, improvements are hoped to be shown by examining revolutionary processes.

INDUSTRIAL ENERGY CONSERVATION ACHIEVED

Some of the energy conservation potential noted by Chiogiogi has already been achieved through housekeeping and retrofit measures. In 1974 the Federal Energy Administration initiated a voluntary program to conserve energy in the industrial sector. The program, known as the Voluntary Industrial Energy Conservation Program, established target efficiency improvements for 1980 for each of the major industries in the manufacturing sector. If the industries achieved their goals, the consumption of energy could be reduced by an estimated 1.2 million barrels per day (Sawhill 1976). The 1980 targets and the gains actually realized by 1979 are summarized on Table 1.3. The table shows that several of the industries were able to exceed their goals by 1979. For example, the chemicals industry exceeded its efficiency improvement target of 14% by more than 8%. The petroleum and the food processing industry exceeded their goals by more than 2 and 3%, respectively. The remaining industries are within 3 to 4% of the targeted improvements. The relationships between the efficiency improvement and the post-oil embargo (1973) stock are shown graphically in Figure 1.1.

NEED FOR FURTHER RESEARCH

These energy efficiency improvements were largely achieved through housekeeping improvements and through changes to more efficient equipment. Additional increases in energy efficiency will require developing and implementing new technologies, and additional major improvements are likely to require major process changes. Thus, the possibilities for revolutionary industrial materials processes pose a major challenge for innovative thinkers. The breadth of processes has only been lightly explored, yet the potential for rewards is immense.

TABLE 1.3. Summary of Status of Industrial Energy Conservation (NMAB 1982)

	1980 Energy Efficiency Improvement Target (%)	1979 Energy Efficiency Improvement (%)	Energy Saved (quads)
Chemicals and allied products	14	22.1	0.84
Primary metals	9	7.8	0.26
Petroleum and coal products	12	14.7	0.44
Stone, clay, and glass products	16	12.9	0.15
Paper and allied products	20	16.9	0.19
Food and kindred products	12	15.3	0.08
Fabricated metal products	24	21.5	0.01
Transportation equipment	16	23.4	0.10
Machinery, except electrical	15	24.7	0.03
Textile mill products	22	17.7	<u>0.03</u>
			2.13

FIGURE 1.1. Relationship Between Efficiency Improvement and Post-Embargo Capital Stock (Belzer 1982)

The primary sources of additional research into energy conservation will be the industry and DOE. Industrial spending on R&D is highly variable among industries. The R&D funds are also generally channeled into several areas, of which energy conservation is but one. Although, as Figure 1.2 shows, the price of various forms of energy has increased substantially over the past several years, other areas have typically received more immediate priority. These areas of R&D include product expansion, process improvement, and regulatory compliance.

In Business Week's annual survey of major manufacturing companies (July 1982), they noted that industry overall invested an average of 2% of their sales on R&D in 1981. This percentage was largely unchanged from 1980. By contrast, investment in many of the major energy-consuming materials processing industries was about 1% of sales or lower. The R&D investments of several industries are shown in Table 1.4. Expenditures by cement and concrete companies were not even large enough to meet the survey cutoff point of 2% of sales or 1 million dollars. O'Hare and Salzano (1981) indicate that the cement industry only invested 0.03% of sales into R&D and the concrete industry 0.01% of sales. The only major materials processing industry that displayed a more significant investment in R&D was chemicals, which invested 2.5% of their sales.

Although many of these evolutionary changes, such as the use of the continuous casting of steel or the direct reduction of iron, will add to incremental improvements in efficiency, they can only be incremental. In addition, these technologies will only bring the U.S. up to par with foreign competition. To recapture the technological lead and to achieve further dramatic improvements in energy efficiency, revolutionary changes will be required. Many of the changes will require long-term research and little such research is under way.

The area of revolutionary materials processes will capture greater domestic attention as the energy efficiency and overall productivity of U.S. foreign competitors continue to accelerate. In the iron and steel industry, Germany and Japan are generally recognized as the world's leaders; in pulp and paper, the Scandinavians are the most advanced; in cement, the Japanese again possess

* NATURAL GAS data for 1975 through 1979 is based on the Dept. of Energy EIA Monthly Energy Review information for industrial users. This information has been discontinued. Beginning with data for the First Quarter, 1980 data are based on uniform values for natural gas published by the Bureau of Labor Statistics.

March 1982

Coal data are based on 6,000 Btu coal figures published by the Bureau of Labor Statistics and Survey of Current Business.

FIGURE 1.2. Comparison of Selected Fuel Costs (EIA 1982)

TABLE 1.4. Industrial R&D Expenditures in 1981

<u>Industry</u>	<u>Percent of Sales Spent on R&D</u>
Steel	0.6
Paper	0.9
Textiles	0.4
Food and Beverage	0.7
Cement	0.03
Concrete	0.01
Chemicals	2.5

the most efficient equipment; in textiles, Switzerland and Germany appear to be the most advanced; in food processing, the Europeans seem to be in the lead. The only industries in which the U.S. might be regarded as the most advanced are petroleum refining and chemicals. However, the chemical industry is so diverse that each subsector would have to be evaluated separately. A report by Hagler, Bailly and Co. (1981) of R&D in industrial energy conservation that is sponsored by foreign governments noted "Because several industries in Germany, France, and Japan are already among the most energy-efficient in the world, the R&D in these industries is shifting more and more toward the development of totally new technologies and processes (rather than components) to improve energy efficiency further. This shift will in all likelihood result in overall--and not just energy-related--productivity improvements." Therefore, to regain an internationally prominent position in the face of restrictive private sector R&D budgets, the U.S. would be well-advised to seriously consider the potential of revolutionary industrial materials processes.

The following section of this report outlines the scope and methodology used in this study. Section 3 presents the candidate processes identified in the eight materials processing industries investigated as well as a discussion of some generic ideas that may revolutionize certain processes. Finally, Section 4 summarizes the results of this study.

2.0 METHODOLOGY AND SCOPE

A systematic methodology is critical to any study to ensure that the efforts are effectively directed toward the goals. Understanding the methodology reveals the focus of the goals and the limits of the study. The methodology is also useful in illustrating the general philosophy that motivates the study. In studies that delve into very broad areas or that are conducted on a tight budget, the methodology becomes even more critical; this study was subject to both conditions.

In identifying candidates for the more efficient use of energy, two overall approaches are typically used (Hopp et al. 1981): 1) the technology push or exploratory approach, and 2) the demand pull or normative approach. The exploratory approach begins with the capabilities of a technology and looks forward in time to its ultimate uses. That is, the development of the technology preceeds the identification of its end-use applications. The normative approach begins with the desired end application and works backward in time to define the needed technology developments. That is, the identification of a need preceeds and motivates the development of the technology.

Initially, the industry- and process-specific orientation of this study makes it a clear candidate to follow a normative or needs-driven approach. However, the diverse nature of certain industries, notably chemicals, revealed that a technology push approach was more appropriate. Therefore, both approaches were used.

As mentioned in the introduction, revolutionary materials processes is an area that has been frequently described as possessing the potential for significant energy and productivity improvements. Given the age of some of the processes, this potential has been cited as essentially being intuitively clear. However, little work has been performed in more specifically exploring this potential across the materials processing industries. This study focuses on overviewing the industries to illustrate the breadth and extent of the development of these processes. The primary concern in undertaking the study, therefore, was identification. The identification consists of three primary elements. First, the literature was reviewed for all reports and articles

that addressed energy conservation in each of the major materials processing industries. The second source of information was industrial energy conservation experts from the industry, academia and national labs. These individuals were approached both for specific ideas as well as for other sources where ideas might be found. The third resource was a preliminary in-house review of the major energy-intensive processes for general alternative schemes. Because the study's objective was to investigate the number of ideas that have been suggested, the study focused on breadth rather than depth.

To help define the state-of-development of the candidate evolutionary processes, specific types of information were identified. In addition to the process description, these types of information included the process or processes displaced, the energy savings potential, other advantages of the process, the major technical problems, and the level of current research. Although not all of the information could be found, that lack of information helped to define the extent of apparent knowledge or development.

As discussed in the introduction, there does not appear to be a clearly agreed upon definition for the term revolutionary process. For this study the term will be defined as a discontinuous conceptual change that eliminates an irreducible cost of the performance of the current service. In contrast, evolutionary techniques involve incremental improvements in existing processes. The long-term criterion would exclude ideas that are developmental and demonstrative.

When attempting to assess the overall attractiveness of any processing alternative, including a revolutionary process, production factors in addition to energy will also be very important because the overall productivity improvement will ultimately measure attractiveness. These factors include capital, labor, and materials costs. This study will, however, focus upon energy savings.

In this study, we have tried to include as many major ideas for revolutionary materials processes as was possible because part of the benefit of an effort such as this is in inciting additional discussion and debate that may uncover more ideas. Because we are concerned with a breadth of candidate processes, we did not limit the identification to those processes that have

been technically proven by laboratory or other hardware testing. Some of the ideas identified appear technically achievable yet have not advanced beyond the conceptual stage. Selecting appropriate ideas was difficult because we wanted a broad list of innovative approaches yet did not want to include any ideas that are not technically credible. Therefore, it is important to bear in mind that this is an exploratory study, not intended to be a comprehensive review, but an illustration of some of the potential for energy conservation through revolutionary processes requiring long-term research.

3.0 INNOVATIVE INDUSTRIAL MATERIALS PROCESSES

This section contains discussions of the innovative and revolutionary processes that were identified in each of the industries investigated in this study: iron and steel; aluminum; chemicals; petroleum refining; pulp and paper; food and kindred products; stone, clay and glass; and textiles. Technologies that can be applied to several end uses, known as generic technologies, are also discussed.

Each of the industrial sections is organized into an introduction, a discussion of each of the processes identified, and in some cases a more detailed description of a selected process with particular potential. The introduction of each industry contains discussions of the overall industrial energy use, energy intensiveness, the age of production equipment, and the general ability of the industry to perform research. The descriptions of each of the processes identified contain discussions of the processes displaced, the energy saving potential, current research, major technical barriers, and other advantages of the process. Due to the infancy of some of the processes discussed, not all of this information was always available. In these cases the processes are detailed to the extent possible. The selected process description deals with each of these topics more thoroughly.

The discussion of generic processes includes a review of the technologies that were uncovered during the investigation and that are potentially applicable to a wide range of uses.

3.1 IRON AND STEEL

The basic iron and steel processing sequence has followed the same pattern for the past 100 years. Figure 3.1 shows a schematic sketch of the traditional ironmaking-steel processing sequence, which is used for producing 700 to 900 million tons of steel annually in the world, and 70 to 100 million tons per annum in the U.S.

As shown in the figure, the steps involved in iron and steelmaking include preparing coking coal and the iron ore, smelting iron in a blast furnace, producing steel in a steelmaking furnace, and casting and forming steel into the

FIGURE 3.1. Conventional Iron and Steelmaking Processing Sequence

desired end products. The blast furnace has been used for iron smelting for hundreds of years and is by far the largest energy-consuming step in iron and steelmaking. As Figure 3.2 shows, the step accounts for 40% of the energy used in the overall process. The steelmaking furnace is also shown to be a major energy consumer, accounting for 10% of the overall energy.

Figure 3.3 shows that the steelmaking furnace has gone through several evolutions since the inception of the Bessemer furnace in the early 19th century. After the Bessemer furnace reached its peak in the early 20th century, it was slowly replaced by the open hearth furnace, which provided greater flexibility. By the middle of the 20th century, the open hearth furnace began to be replaced by the more efficient basic oxygen furnace (BOF), which is currently the primary furnace used for steelmaking. The mid-20th century also witnessed the development of the electric arc furnace, which is currently being used in smaller plants to process scrap and direct reduced iron.

Steel products are currently produced by two basic types of plants: large integrated plants and small nonintegrated producers. Integrated producers operate on a large scale (1 to 8 million tons per annum) and begin with iron ore and coal as the basic raw materials. These materials are charged to a blast furnace to make iron. The iron is then fed to a basic oxygen furnace (BOF, Q-BOP, etc.) to produce steel, which is then cast into ingots or continuously processed and finally deformation processed (i.e., rolled) to give the desired finished products.

The nonintegrated producers (sometimes termed mini-mills), operating on a smaller scale, typically produce 200,000 to 2,000,000 tons per annum. These plants use scrap or sponge iron pellets as the starting materials, which are melted in electric furnaces to produce liquid steel. This material is then processed the same way as the BOF product in integrated plants. In general, the nonintegrated plants, which compose about 25% of the capacity in the U.S., are more modern than the integrated plants and tend to produce a much more limited product line.

A typical integrated steel plant in the U.S. requires about 8 man-hours per ton of product and 33 gigajoules per ton of product (most of which is coal

FIGURE 3.2. Estimated U.S. Level-1 Energy Consumption by Major Process Units in 1976 (Arthur D. Little, Inc. 1978)

FIGURE 3.3. Changes in Steelmaking Methods in the United States (1860-2000) (Trout 1980)

or coal based). The cost of production is about 450 to \$500 per ton, of which labor and energy account for about 35 and 30%, respectively.

The corresponding figures for the mini-mills or nonintegrated producers would be as follows: 2 to 3 man-hours per ton of product, and 6 to 10 gigajoules of energy per ton of product (fossil fuel equivalent of electric power). The cost of production for a scrap-based operation would be about 250 to \$300 per ton plus interest on capital.

It is not entirely fair to compare the integrated and the nonintegrated producers directly because the latter use scrap, which has to be only melted rather than smelted as needed for the iron ore. Furthermore, the more limited product line also allows considerable economies. Nonetheless, the mini-mills

are perceived to be generally more efficient and more profitable operations than those of most of the integrated producers.

The European figures for labor and energy consumption are thought to be comparable to those in the U.S., with labor being somewhat higher and energy consumption being somewhat lower. The European production costs are hotly disputed and would be difficult to assess but are likely to be in the range of or somewhat higher than in the U.S.

The previously given figures for integrated steel plants in the U.S. (and in Europe) may be sharply contrasted with those attainable in the modern facilities in Japan, Korea, and Taiwan. Plants in these countries typically require only 2 to 4 man-hours per ton of product and 22 to 24 gigajoules per ton of product.

Clearly, the reduced labor and energy requirements attainable in the modern plants provide a considerable competitive edge. However, the construction of new modern plants using the existing technology is unlikely to be the answer in a developed country, because the capital cost of such an installation is estimated to be in the range of 1500 to \$1800 per annual ton capacity. Allowing for current interest rates, the cost attributable to servicing this debt would overwhelm any savings; thus, the construction of the most modern facilities using existing technology will not provide a solution to this dilemma. This situation should provide a clear-cut motivation for the U.S. to develop alternative technologies because the survival of the steel industry could depend on it.

Japan, which is currently at the forefront of iron and steelmaking technology, is also strongly motivated to develop new processes to maintain its technological leadership. Considerable evidence indicates that significant resources are being devoted to such a program.

The U.S. steel industry is faced with very serious problems, partly because many of its facilities are obsolete. If the U.S. could implement new concepts in ironmaking and steel processing, modernization could be achieved very cost effectively and we possibly could pass existing competitors who presently may have modern conventional steelmaking facilities.

3.1.1 Alternative Industrial Materials Processes

The primary motivations for developing radically innovative steelmaking technologies, in the order of perceived priorities, are as follows:

- to reduce capital cost requirements
- to reduce labor costs
- to reduce energy consumption
- to produce better quality products
- to allow the use of cheaper (more readily accessible) raw materials.

Figure 3.4 gives comparative costs of energy, labor and capital in steel-making and shows that the primary end of the conventional processing sequence is highly energy intensive, while the finishing end is more labor intensive. The capital cost requirements are about the same for these operational sequences.

FIGURE 3.4. Comparative Costs of Energy, Labor, and Capital in the Primary and Finishing Ends of Steelmaking

The principal ideas suggested for radically innovative steelmaking and steel processing operations are discussed below. Two of the most promising technologies will be discussed in greater detail in a subsequent section.

Direct Steelmaking

In this group of processes, shown in Figure 3.5, iron ore, a carbonaceous fuel, and oxygen are fed to a vessel holding molten iron. The ore is melted and is made to react with coal (char or other carbon source) to produce molten iron or semisteel. The heat of reaction (and of melting) is supplied by the combustion of additional coal with oxygen and possibly by the partial combustion of the CO produced in the freeboard of the vessel.

Direct steelmaking is potentially very attractive because it offers the possibility of a greatly reduced capital cost (by eliminating coke making, ore preparation, the ironmaking step, and at least part of the steelmaking step). Direct steelmaking is regarded as one of the potentially most important new technologies and will be discussed in detail in Section 3.1.2.

Ore-to-Powder Systems

Ore-to-powder systems have the potential for producing steel products from iron ore by completely eliminating the energy-intensive coke ovens, blast furnaces, and steelmaking furnaces that are required for conventional processing. One approach to an ore-to-powder system is shown in Figure 3.6. In ore-to-powder systems the iron ore first is super-beneficiated and then partially reduced. Then, magnetic separation is used to separate the magnetite, followed by chemical leaching to remove impurities. The material is then dried, further reduced, and passed once more through magnetic separation to produce the product iron powder. The powder is then rolled into steel products via a powder metallurgical route.

In principle, the ore-to-powder schemes offer the potential for lower capital costs, lower energy consumption, and production flexibility. A very low capital cost of 600 to \$800 per annual ton capacity has been claimed. In addition, an energy savings of 40% over conventional processes may be achievable. Furthermore, the process could be well suited for smaller scale (e.g.,

FIGURE 3.5. Direct Steelmaking

FIGURE 3.6. One Proposed Ore-to-Powder Steelmaking Process (Szekely 1980)

mini-mill type) operations. Other schemes that eliminate the chemical leaching requirement have been proposed, potentially saving additional capital, energy, and production time.

One of the primary technical barriers to this process is the need for highly refined magnetic separation. Iron ore contains approximately 5% impurities. The finished product is required to contain less than 0.05% impurities, a one-hundred fold reduction. Further, magnetic separation is normally used to separate a small amount of material from a large amount of nonmagnetic substance. The ore-to-powder process requires just the opposite.

In the 1960s, several unsuccessful attempts were made by several major U.S. steel producers (e.g., Bethlehem Steel, Republic Steel, and ARMCO) to realize ore-to-powder schemes. Currently, very little effort is under way in this area.

Ore-to-powder schemes would represent a high-risk high-reward venture, and an exploratory study in this area should be encouraged.

Plasma Steelmaking

Plasma arc steelmaking, sketched in Figure 3.7, has been under study for many years. This process involves generating a stable arc between two electrodes. Because of the very high temperatures attained in this arc, the reactions among the feed materials supplied into the arc proceed very rapidly.

The earlier ideas embodying plasma arc steelmaking suggested feeding a mixture of iron ore and a reductant (natural gas or coal) into the plasma furnace to obtain molten semisteel.

Plasma steelmaking has the potential for eliminating a significant fraction of the primary steelmaking operations. However, it requires a large amount of electric power to cover both the endothermic heat requirement of the reaction, shown below, and the sensible heat requirements.

This thermal energy, equaling about 2,000 to 3,000 kWh/kg, would be comparable or even higher (on a thermal equivalent basis) than that required in the

FIGURE 3.7. Plasma Steelmaking

conventional systems. This thermal energy would have to rule out the original ideas for using plasma steelmaking for producing low carbon steels.

One of the major drawbacks that would inhibit the scaling-up of production is the size of the plasma guns. Plasma guns are manufactured to a maximum size of 3 MW, whereas electric arc furnaces are in the 60 to 80 MW size range. There may be a fundamental limitation to the size of the plasma gun, and if this limitation is in the current range, this steelmaking process would require many modular units. However, some form of plasma or electrically derived thermal energy may be useful for the partial smelting of iron ores. This possibility is being developed in Sweden in the form of three new processes: the ELRED, the INRED, and the PLASMASMELT systems.

The ELRED, INRED, and PLASMASMELT Processes

These three Swedish processes have the common feature that a partially reduced (prereduced) iron powder is being smelted by a reaction with pulverized coal. The latent heat of reaction is supplied by either a plasma system (ELRED and PLASMASMELT or SKF system) or by submerged resistance heating (INRED).

These systems are potentially attractive because they would reduce the total capital cost required for producing molten steel, particularly for smaller scale operations. Of these three systems, the INRED system appears to be the closest to commercialization, with extensive pilot-scale trials having been conducted at MEFOS in Sweden. There are also plans for the construction of a plant in Canada.

One of the major attractions of these processes in Sweden is the apparent reduction in energy use. Modern technology can produce steel with an energy intensity of 4000 kWh per ton of product. The ELRED process can produce steel while using 3300 kWh per ton and the PLASMASMELT process is predicted to require only 2420 kWh per ton. These values compare with a theoretical minimum of 1700 to 1800 kWh per ton.^(a)

(a) Personal communication with Johanson (1982) from the Royal Institute of Technology, Sweden.

A drawback to using these processes in the U.S. is their electricity requirements. Of the 3300 kWh used to produce a ton of product with the ELRED system, 350 kWh is electric. For the PLASASMELT system, of the 2420 kWh used to produce a ton of product, 1160 kWh is electric. In a country such as Sweden with plentiful access to hydroelectricity, these fractions of electricity use are not as important as in the U.S., where much of the electricity is generated from petroleum and coal power plants. When the loss of energy from electricity generation is accounted for, little overall energy conservation potential exists. The significant electric component of all 3 of these systems probably would be a serious impediment to commercialization in areas where the power generation costs are quite high, such as in the U.S.

These systems also involve considerable complexity and will require many untried components to be used in combination. Further, labor costs most likely would not be reduced. Therefore, the more detailed examination of direct steelmaking operations is judged to have a much higher priority.

Direct Casting

In direct casting, shown in Figure 3.5, molten steel would be cast into shapes that would approximate that of the final desired product; therefore, the direct casting of plate, strip, or bars may be possible. As the figure shows, direct casting would eliminate a significant portion of the deformation processing (i.e., rolling) steps, together with the attendant reheating furnace operations.

Direct casting might save as much as 30 to 40% of the total capital cost, 20% of the energy consumption, and 20 to 30% of the total labor cost. This appears to be a very attractive scheme, which definitely deserves detailed attention and will be discussed in Section 3.1.2.

Electroforming

In electroforming operations the starting point is an electrolyte containing some ferrous salt, such as FeCl_3 . The salt is then electrolyzed to deposit a steel sheet or foil on a cathode, while chlorine gas evolves at the anode. This chlorine is then recycled to produce the electrolyte.

The potential attractiveness of electroforming would be the complete elimination of the conventional ironmaking and steel processing sequence, together with the possibility of producing thin sheets or foil of very high purity in essentially one step. The difficulties anticipated for electroforming would partly be due to the very high energy consumption (approximately 3000 kWh) and the high capital cost, caused by the very low processing (i.e., deposition) rates. Many modular units would be required for large-scale production. These two factors, together with the high cost of producing the iron chlorides for the electrolyte, should rule out electroforming as a serious contender for producing steel sheet or foil at high tonnage levels.

3.1.2 Investigation of Selected Processes

Among the candidate revolutionary processes discussed in the preceding section, two processes stand out as deserving further development: direct steelmaking and direct casting. These processes appear to offer a combination of 1) the potential for maximum impact in terms of capital, energy, and labor savings and 2) a high degree of feasibility based upon available evidence. Because of this positive rating, these technologies will be discussed further in this section.

Direct Steelmaking

Direct steelmaking, as shown in Figure 3.1, involves in the injection of iron ore, coal and oxygen into a bath of molten iron. The principal reactions involved are the reduction of the iron oxide to iron and the combustion of carbon with oxygen to cover the endothermic heat requirements.

Such a process would be extremely attractive because it would replace the coke-making ore preparation facilities, the iron blast furnace, and at least part of the BOF vessel, with a single vessel. This would afford very appreciable savings in capital, energy and labor.

Direct steelmaking may save as much as 30 to 35% of the capital cost, 20 to 30% of the energy consumption and 10 to 15% of the labor cost associated with the conventional ironmaking steel processing sequence. The process also could operate at levels of about 250,000 to 1,000,000 tons per annum, appropriate for mini-mill operations.

The principal problems in implementing direct steelmaking systems would be containment. Specifically, the problem involves the durability of refractory linings in the high-temperature, oxidizing environment. This presents both a materials problem and a problem with the physical design of the process. Providing for oxidizing and reducing reactions in the same reactor may also be a problem. However, this latter problem probably could be avoided by having a separate container for the ironmaking operation.

There is a strong interest in this process in both Germany and Japan. In a recent article published by the Sumitomo Steel Corporation (Tanoue 1981), the feasibility of gasifying coal by injecting a mixture of coal and oxygen into molten iron has been demonstrated in a pilot-scale installation. Direct steelmaking is unlikely to pose much more serious containment problems.

Direct steelmaking should be actively pursued by defining a research program, aimed at the examination of the fundamentals and this program should be extended to include work on at least a pilot scale (30 to 50 ton vessels).

Direct Casting

As discussed earlier, the direct casting of finished shapes (or near final shape specimens) would offer the potential of eliminating most of the deformation processing steps, the reheating furnace operation and a significant fraction of the labor costs. Thus, when compared with conventional processes, direct casting may save as much as 30 to 40% of the capital cost, 20% of the energy consumption and 20 to 30% of the total labor cost. Its overall impact on steel processing technology could be revolutionary, comparable to that of direct steelmaking.

The principal problems possible in implementing direct casting schemes are as follows:

1. Obvious mechanical problems have to be overcome in feeding liquid metal to a caster in a spatially uniform manner.
2. To process the material at rates compatible with conventional processing operations, a direct caster may have to operate at speeds comparable to a hot strip mill.

For example, if we have a linear casting velocity of 2 m/min for a slab caster, producing 250 m thick slabs, a direct strip or plate caster, producing a 5 mm thick sheet would have to operate at a linear velocity of 100 m/min.

3. Mechanical working, which is inherent in rolling operations, is thought to be an essential component of steel processing. Thus, eliminating most of the rolling operations may not be feasible.
4. The proper way to critically assess most of these objections would be possible only through a pilot-scale operation including finishing and detailed product evaluation, which could be quite expensive.

Despite these potential problems, the impact of direct casting on steel processing technology could be enormous; furthermore, the feasibility of this process concept has been demonstrated at the Jones and Laughlin Steel Corporation in the early 1970s. For this reason, a substantial effort in this area would be fully justified.

3.2 ALUMINUM

The aluminum industry is one of the largest industrial consumers of energy in the United States. A breakdown of energy consumption for various production operations in the aluminum industry is provided in Table 3.1 (Aluminum Association 1981).

TABLE 3.1. Aluminum Industry Energy Consumption in 1980

<u>Operation</u>	<u>Energy Consumed (trillions of Btu)</u>
Bauxite	0.25
Alumina (Bayer Process)	115.02
Smelting (Hall-Heroult Process)	747.10
Holding, Casting, Melting	61.54
Mill Products	116.65
Other Fabrication	<u>7.35</u>
Total	1047.91

Since 1972 the aluminum industry has been carrying out an aggressive energy conservation program through its trade group, the Aluminum Association. The current program is being carried out in cooperation with government departments and agencies. The program covers all operations itemized in Table 3.1. Since 1972, the energy consumption rate has been reduced by over 13%, excluding the extra energy needed to meet EPA regulations. The goal is to achieve 20% energy savings by 1985.

Reducing alumina to primary aluminum metal using the Hall-Héroult smelting process (SIC-3334) alone requires over 70% of the energy required for the whole industry. Most of the energy required for smelting is in the form of electricity, as indicated in Table 3.2 (the Aluminum Association 1981). The average U.S. smelter consumes about 7.5 kWh per pound aluminum and a new smelter can operate close to 6 kWh per pound.

The process cell, shown in Figure 3.8, involves alumina (Al_2O_3) dissolved in a bath of molten cryolite (Na_3AlF_6) with fluoride additives. The alumina decomposes electrolytically into aluminum and carbon dioxide at

TABLE 3.2. Smelter Energy Consumption in 1980

<u>Energy Form</u>	<u>Energy Consumed (trillions of Btu)</u>
Electricity - Thermal (purchased)	383.47
Electricity - Thermal (generated)	149.36
Electricity - Hydro	109.08
Petroleum Coke	69.30
Pitch	19.50
Natural Gas	20.03
Residual Oil	0.54
Distillate Oil	0.35
Lube Oil	0.27
Propane and LPG	0.24
Gasoline, Kerosene	0.22
Coal and Miscellaneous	<u>(0.25)</u>
	752.61

FIGURE 3.8. Cross Section of Hall-Héroult Aluminum Reduction Cell
(Hittman 1980)

970°C in a carbon-lined steel vessel. The electricity enters the bath through the carbon liner and exits through the consumable carbon anodes.

Since the Hall-Héroult process was discovered in 1886, it has been the sole process used for smelting aluminum in the U.S. The process has been improved substantially through the years but still has room for further improvement. A large amount of effort and money has been spent over the years to develop a better and more economical process, but no alternative process has yet reached the commercial stage. All currently planned new smelters will still use the Hall-Héroult process.

Research for the aluminum industry in the smelting area is sponsored primarily by the aluminum companies themselves. Government-supported research was performed in earlier years by the U.S. Bureau of Mines and in recent years is being provided by DOE.

During the past 20 years the energy efficiency of smelting has been improved in the areas of cell computer control, anode and cathode improvement,

increased cell size, emission control, mechanization, improved current efficiency and electrolytic composition, electrical improvements, and cell heat balance (Russell 1981a). Energy conservation most likely will continue to be gradually increased in these areas.

Recent research efforts towards major improvements in the Hall-Héroult process have been directed toward developing an inert anode (nonconsumable) and more electrically conductive inert cathode liner materials. Successful development in these two areas, along with a more superior side wall material, may reduce electricity consumption by up to 30%. Further, additional energy will be saved by eliminating the fabrication of consumable anodes (Arthur D. Little 1979; Russell 1981a; Hittman Associates 1980). This would be a major breakthrough, considering that materials research has been under way in these areas for several decades.

3.2.1 Advanced Aluminum Processes

For over 90 years, the Hall-Héroult process has remained the sole commercial aluminum smelting process in the U.S. A large effort has gone into finding an improved replacement process; hundreds of patents have been filed. In addition to alternative electrolysis processes, efforts have been made to develop carbothermic processes to reduce alumina or aluminous ores. Perhaps the most revolutionary alternative process involves the carbothermic production of aluminum from low-grade ores. This process virtually eliminates the use of electricity in aluminum production. This carbothermic process and other advanced alternative processes are discussed below.

A schematic-flow diagram of the conventional aluminum processing sequence and the manner in which revolutionary alternatives tie in is shown in Figure 3.9.

Carbothermic Reduction of Ore

The reduction of ore rather than pure alumina has several advantages. Ore reduction can eliminate the Bayer process to refine alumina, can use an abundance of lower purity ores, results in a lower thermodynamic activity of aluminum in alloys, and reduces the capital and manpower requirements. Also, no

FIGURE 3.9. Conventional Aluminum Production Process and Advanced Alternative Processes^(a)

(a) Solid lines indicate the conventional process and dotted lines indicate the alternative process.

fluoride emission problems are encountered. However, these advantages are partially offset by the additional steps needed to refine pure aluminum from the alloy.

Recently, Mitsui Alumina of Japan announced that they have developed a method of smelting and refining aluminum which eliminates the use of electricity (Marketing Perspective 1982). The Mitsui method uses coking coal to reduce aluminum from bauxite and other ores in much the same way as is done for iron in the steel industry. A sketch of the Mitsui reactor is shown in Figure 3.10. An advantage of the process is that ores with low alumina content can be used. In the Mitsui process, alumina, silica and iron oxide-bearing materials are mixed with coal in 600 to 900°C to form alumina-bearing coke briquettes. The temperature of these briquettes is then increased to 2000 to 2100°C to produce aluminum, silicon and iron-containing alloys. The alloys are scrubbed by a molten lead spray directly after the formation of the alloys and are thereby converted to a lead-aluminum alloy. Aluminum is then separated from the lead by liquidation and purified by fractional distillation (Kawahara 1981). The process produces ingots of 99.9% purity.

This development is considered a major breakthrough for Japan, which has exorbitantly high electricity costs because 75% of their power plants are oil-fired. Work on a large-scale test facility is being undertaken by Mitsui and three other companies.

Alcoa and DOE, in a cooperative venture, have also been investigating the technical feasibility of producing aluminum-silicon alloys by carbothermic reduction. Alumina-silica ores are reduced through combustion heating with coal-based coke (Russell 1981b). The energy consumed can be relatively low if credit is taken for the by-products and carbon monoxide used either to generate electricity or to produce heat.

Many other concepts for producing aluminum from ore through carbothermic reduction have been explored (Grjotheim and See 1979; Arthur D. Little 1979; Grjotheim and Welch 1981; Russell 1981b). However, the only commercial aluminum carbothermic operations, if any, are probably located in the U.S.S.R.

Carbothermic Reduction of Alumina

Reducing alumina with carbon at high temperatures (>2000°C) has some advantages. As with ores, the capital and manpower requirements may be reduced and the fluoride emissions will be eliminated. A serious problem with developing this process has been the formation of aluminum compounds with carbon, oxygen, and nitrogen.

FIGURE 3.10. Mitsui Carbothermic Aluminum Production Process (Kawahara 1981)

Many concepts using this process have also been worked on (Russell 1981b; Grjotheim and Welch 1981; Menegoz 1979; Grjotheim and See 1979). One of the most recent was a plasma process reacting alumina and carbon powders to aluminum and carbon monoxide, but it is not known to have undergone large-scale testing. Development of plasma processing for producing crude iron is well under way and shows promise (News Release 1981). Using the plasma process to

produce aluminum, which is a much higher valued product than iron, has enough merit to be more actively investigated.

No commercial-scale process for reduction of alumina by carbothermic means is known to exist.

Alcoa Aluminum - Trichloride Electrolysis

The only alternative smelting process that has received large-scale testing and that is closest to commercialization is the aluminum-trichloride electrolysis process being developed by Alcoa (Russell 1981a; Hittman Associates 1980; Forberg 1981; Grjotheim and Welch 1981; Grjotheim and See 1979; Arthur D. Little 1979). As shown in Figure 3.9, this process would be a direct substitute for the Hall-Héroult process. Figure 3.11 shows a schematic of the trichloride electrolysis cell.

FIGURE 3.11. Trichloride Electrolysis Cell
(Russell 1981a)

The Alcoa process has several advantages over the Hall-Héroult process. The Alcoa process requires far less electricity (~4.5 kWh per pound, or a 40% reduction from the average smelting energy); it does not require consumable anodes; it is free of fluoride emissions; and it may have lower capital and operating costs. The main disadvantage is that fuel oil consumption in the chlorination step offsets a large amount of the electric energy savings. Therefore, the total savings may not be significant. Technical difficulties most likely will be in handling the very corrosive aluminum chloride, maintaining the purity of aluminum chloride in the bath, and maintaining a water- and air-free environment in the reduction cell.

Aluminum Sulfide Electrolysis

This process involves the reaction of either alumina or bauxite with coke and sulfur to form Al_2S_3 (Arthur D. Little 1979; Grojtoheim and Welch 1981; Hittman Associates 1980). This intermediate product would then be electrolytically reduced to aluminum and the sulfur recovered. The estimated electrical energy required for the reduction step is about 3.8 kWh per pound (15% less than the Alcoa process, and 50% less than average conventional processing requirements). However, carbon requirements are even higher than in the Hall-Héroult process. The viability of this process depends upon the relative ease of producing Al_2S_3 and preventing environmental problems. Recovering sulfur and using closed cells to prevent moisture and highly toxic H_2S from forming also may present problems. Considerable development is required for this process. Basic research on this process recently has been performed at Argonne National Laboratory.

Other Processes

The aluminum industry has not suffered from a shortage of ideas for major process changes. Numerous alternative smelting processes have been worked on in the past few decades (Russell 1981a; Arthur D. Little 1979; Grjotheim and See 1979; Hittman Associates 1980; Grjotheim and Welch 1980). Some of the investigated processes are as follows:

- Alcan: monochloride purification of directly produced aluminous ores

- British Aluminum Company, Kaiser: refractory hard metal cathodes in Hall-Héroult cells
- Pechiney: direct reduction process plus vacuum decompositions
- Reynolds: direct reduction followed by centrifugal purification
- Toth Process: reduction of AlCl_3 by manganese
- Aluminum nitride thermal decomposition at 2700°C
- Battelle Geneva: nitride electrolysis
- Bauxite chlorination to eliminate Bayer process and chlorinization step in Alcoa process
- Electrolysis of aluminum halides and organometallic derivatives in nonaqueous solvents
- Oak Ridge National Laboratory: recovery of aluminum chloride from fly ash.

3.3 CHEMICALS

In 1972, the chemical process industry (CPI) consumed 3.54 quads of energy. In 1981, the CPI has decreased its total energy consumption 11.2% to 3.15 quads (excluding feedstocks) (C&EN May 1982a). This savings is particularly significant when coupled with production increases that averaged 6% per year during this period for an overall increase in production of 50% since 1972. The increased production capacities and corresponding positive financial health in the industry have enabled the CPI to implement many basic incremental energy savings opportunities such as equipment improvements, waste heat utilization devices, process control improvements, and a variety of specific process improvements.

The chemical industry comprises many separate product industries, each of which has unique, process-specific requirements. The number of product-specific processes in the chemicals industry is more diverse than in any of the other major materials processing industries. The major categories of chemicals produced include industrial organics, industrial inorganics, plastics and synthetics, and agricultural chemicals. The primary chemicals composing

industrial organics are the cyclic intermediates such as styrene, ethyl benzene, and phenol; and the category of miscellaneous products such as ethylene, methanol, and formaldehyde. The primary categories within industrial inorganics include the alkalies and chlorine, and miscellaneous inorganics such as sulfuric acid, sodium sulfate, calcium chloride, and sodium silicate. Plastics and synthetics include subcategories such as plastics and resins, synthetic rubber, cellulosic fibers, and organic fibers, and agricultural chemicals include nitrogenous fertilizers, phosphate fertilizers, and pesticides. Table 3.3 lists the 30 chemical products that consumed the most energy in 1977.

Suggestions for process improvements have understandably been directed toward the large volume processes. Ammonia, for example, which is second only to sulfuric acid on the annual production list (compared on the basis of pounds produced), has had several major process improvements in the last few years. Two of the most recent process developments, the "Purifier" process of C. F. Braun and the Humphrey and Glasgow process, possibly could reduce fuel and feed stock use from 10 to 40% (Burch, Otis and Hale 1979). Other less important processes (in terms of production volume), however, have also been improved. For example, a process for making hydrazine has been recently commercialized by Produits Chimiques Ugine Kuhlmann in France (C&EN November 1981a). Their process is estimated to reduce the energy consumed in making hydrazine by over 60% compared to conventional processes, while increasing the yield from 70 to 90%. These and other reasonably mature technologies will lead the way for continued energy conservation in the CPI during the next two decades.

The CPI, in general, maintains a very active and growing R&D program. During 1980 the CPI spent \$4.5 billion on R&D, of which only about \$30 million was given to university research. The two largest companies in terms of sales, DOW Chemical and DuPont, together accounted for \$1 billion in R&D expenditures during 1980 or nearly one-fourth of the CPI total. The CPI is well known for its large and technically advanced R&D programs and facilities.

3.3.1 Alternative Industrial Materials Processes

The combined complexity and diversity of the CPI make it very difficult to identify and describe the major areas of possible process improvements.

TABLE 3.3. 30 Top Energy-Consuming Products in 1977 (Data Resources, Inc. 1978)

	Intentional Production (billion lb)	Energy Consumption (billion Btu/product)	Percent ^(a)
Chlorine	21.296	365,387	25.4
Ammonia	34.752	223,636	15.5
Methanol	6.453	60,103	4.2
Styrene	6.368	53,522	3.7
Vinyl Chloride	5.836	50,863	3.5
LDPE	6.471	49,763	3.4
Ethylene	25.426	48,047	3.3
Polyvinyl Chloride	5.253	38,665	2.7
Butadiene	1.510	33,582	2.3
Ethylene Glycol	3.675	26,548	1.8
Acrylic Fiber	0.709	26,509	1.8
Acetic Acid	2.158	25,409	1.8
Adipic Acid	1.509	23,490	1.6
Ethylbenzene	7.853	22,326	1.6
Polyethylene Terephthalate	4.368	20,536	1.4
Propylene Oxide	1.866	19,811	1.4
Phenol	2.148	19,035	1.3
HDPE	3.651	18,657	1.3
Polypropylene	2.747	18,499	1.3
Urea	8.991	17,591	1.2
Caprolactam	0.866	17,332	1.2
DMT	2.972	16,645	1.2
Ethanol	1.312	16,617	1.2
Isopropanol	1.844	15,178	1.1
Hexamethylene Diamine	0.878	14,535	1.0
S.B. Rubber (net rubber)	3.076	14,522	1.0
Acetylene	0.416	13,065	0.9
Vinyl Acetate	1.586	12,457	0.9
Polybutadiene	0.795	11,837	0.8
TOTAL		1,303,849	90.5
TOTAL (DRI Petrochemical Model)		1,438,274	100.0

(a) Percent of total consumption in DRI Petrochemical Model.

The CPI represents several hundred different chemicals and drugs, each representing at least one process. In addition, the majority of the process-specific information is proprietary, and new ideas being developed within the industry will not be made public until they are well on their way toward

commercialization. In general, the literature is replete with well-developed, near-term methods for improving specific processes. For example, new processes and technologies from the industry are published semiannually in Chemical Engineering. Long-term technologies, however, are much more difficult to discover.

To maintain this project at a manageable level and still achieve the objective of reporting long-term "revolutionary" process changes, the findings will be discussed in a broad generic fashion. General technologies that are applicable to a variety of specific processes will be described. Each technology will be explained briefly and each explanation will include a description of the technology's advantages, such as its energy-savings potential. Specific processes will also be discussed as example applications whenever possible.

In general, and very simply, any major process in the chemical industry consists of two main elements: a reaction step and a separation or concentration step. Of course, the processing of some chemicals consists of a multitude of both steps mixed together. However, for discussion purposes, the steps will be separated and discussed independently.

For a typical reaction process in the CPI, 70% of the capital costs and 80% of the energy consumed are in the separation and concentration steps (C&EN July 1980a). However, when thinking about ways to improve the energy utilization efficiency of a process, these figures can be misleading. Because the reaction and separation phases are interdependent, changing a reaction can substantially alter the energy requirements of the separation phases. Thus, both are important and must be considered concurrently when determining actual energy savings.

The following sections will first discuss the expected future developments in reaction chemistry and their impact on energy use. This will be followed by a discussion of the separation operations, the specific processes identified, and the energy impact anticipated.

Reaction Chemistry

The reaction step in a chemical process can be loosely defined as the formation of one chemical from another by a transformation of its chemical bonds. Of course, individual reactions are quite different from one process to the next, especially between organic and inorganic processes. Although much R&D work has gone into understanding these reactions in the last 30 years, scientists and engineers are just beginning to understand some of the basic mechanisms involved in many reactions. Such work, in the very basics of chemical reactions, must continue for new advanced processes to reach the applied stage in development.

For a reaction to take place, enough energy must be supplied to break existing bonds and/or to form new ones. Unfortunately, extra energy is wasted in exciting the wrong bonds, resulting in a diffusional loss of energy. Often the reactants must be heated to a very high temperature before the reaction will take place. New developments in reaction chemistry are focused on controlling the use of the energy and focusing it on the appropriate bond or bonds involved. Specifically, a few of the areas of applied research currently receiving attention are biotechnology, photochemistry, catalysts, and advanced reactor design.

Biotechnology. Recent developments in biotechnology should be considered a revitalization of an old industry rather than the creation of a new one. Prior to the discovery of cheap petroleum feedstocks, several chemicals were produced from biomass via fermentation. Today's better understanding of biotechnology opens the way for many new chemicals to be produced. Not only will biotechnology allow more traditional fermentation-derived chemicals to re-enter the market, but newly developed enzymes will allow these products to enter the chemical conversion chains and to compete directly with common chemical processes. Table 3.4 lists a few of the varieties of chemicals that can potentially be replaced with biotechnology. Most of these can be derived from glucose via fermentation, although the aromatic chemicals such as benzoic acid must be derived from benzene or an equivalent. The technology for commercially producing these chemicals using biotechnology is in most cases 10 years or more away.

TABLE 3.4. Potential Bioproducted Chemicals

<u>Compound</u>	<u>Typical Precursor</u>
Acetic Acid	Methanol or Ethanol
Acrylic Acid	Ethylene
Benzoic Acid	Tar Oil
Ethanol	Ethylene
Ethylene Glycol	Ethylene
Ethylene Oxide	Ethylene
Glycerol	Soap Manuf.
Isobutylene	Petroleum
Methane	LNG
Phenol	Coal Tar
Propylene Glycol	Propylene

The major advantages of biologically producing organic chemicals include the use of renewable resources (biomass from variety of sources) as feedstocks (in place of petroleum feedstocks), the need for less extreme process conditions, the use of one-step production processes, and reduced toxic wastes.

Producing chemicals by synthesis often requires high temperatures and pressures to give high yields. Large amounts of energy are consumed maintaining these extreme process conditions. Alternatively, enzymes are used under very mild process conditions, which provide the potential for significant energy savings. In addition, energy is saved by reducing the number of steps in the process. Typical chemical synthesis of compounds require several steps with separations required between each step. In biological systems the microorganisms often complete entire synthetic schemes in essentially one step.

Typical chemical synthesis uses metal catalysts of various types that are not ordinarily limited to solely producing the desired products. Consequently, undesirable side-products are often produced that can cause difficult waste disposal and pollution problems. A genetically engineered organism, on the other hand, can be designed to minimize the production of wastes and to maximize the yield of the desired product. Consequently, biological processes

eliminate many conventional waste disposal problems. The wastes that are produced are usually biodegradable and valuable sources of nutrients (e.g., for use in animal feed).

In principle, virtually all organic compounds can be produced by biological systems. The potential for their use is thus entirely in the hands of the imaginative biotechnologist. Realistically, this potential is tempered by the technology required to take the process from start to finish. Purification or separation is an important part of this needed technology. Most chemical products of fermentation are present in extremely dilute solutions, and concentrating these solutions to recover the desired product is highly energy intensive. Therefore, developing large-scale, inexpensive separations processes will be a major challenge. (This will be discussed further in the section on separation technology). A second technical problem is in maintaining the microbes under the large flow rate processing conditions typical of chemicals production. A third concern that may limit the potential of biotechnology is the need for raw materials. Often the most usable raw materials are also used as food sources, resulting in prohibitive costs.

Biologically produced chemicals will definitely play a viable role in the CPI in the next two decades. As the technology advances, various processes will begin to be cost competitive. Many private companies have well-developed aggressive research teams working to exploit the potential.

Photochemistry. A recent study by the MITRE Corporation (Roberts et al. 1982) indicates that there have been no recent additions of photochemical processing in the CPI with the exception of the greater use of photochemistry in synthesizing and curing polymeric materials and a broader and growing application of UV in water treatment. The report further states that the use of photochemistry in the production of chemicals has decreased largely due to the environmental restrictions on chlorinated compounds since halogenation is a common application.

The potential use of photochemistry is technically rather large, encompassing reactions such as photohalogenation, photohydrosulfidation, photonitrosation, photosynthesis, and others. Several of these processes are already

used commercially. In addition, areas such as photopolimerization and water splitting have been the focus of much activity in recent years.

One field that has received a lot of attention recently is laser chemistry. Lasers are used to activate chemical reactions by selectively exciting certain chemical bonds through the application of wavelength specific energy. As a result, the diffusional loss of energy present in thermally driven reactions is avoided. The fine tuning possible with laser activated reactions gives it potential value in microprocessors, although cost will probably limit its use. Laser chemistry is also being explored for uses in production-scale processes. However, the scale-up from laboratory bench testing to the sizes required by production is anticipated to present major challenges. A major need in laser chemistry, and in photochemistry in general, is the engineering modeling of reactors.

Much of the current research in photochemistry is devoted to understanding reaction mechanisms; very little research is devoted to actual process chemistry. Although new applications for photochemistry will definitely surface in the next two decades, its use will likely focus on very special applications.

Catalysts. A catalyst is simply a substance that forces a series of reactions to dominate so that a specific product results, predominately excluding other products. Catalysts have been used for many years in both organic and inorganic chemistry. Because the purpose of a catalyst is to assist in controlling a given chemical reaction, the use of catalysts has increased as chemists have improved their understanding of reaction theory.

A catalyst must be active and selective and must have chemical and physical stability. Typical catalysts now used in the CPI are compounds of common earth metals such as zinc, copper, iron, etc. These catalysts, applied especially to organic chemistry, are quite well understood. Inorganic chemistry, because of the greater diversity of reactions, is less well understood and consequently, the catalysts are not as widely employed.

The newest developments in catalysts are in rare elements such as tungsten, ruthenium, and molybdenum. For example, a recent discovery (C&EN, July 1981) has demonstrated the ability to split H_2S into hydrogen gas and

elemental sulfur using a combination of cadmium sulfide loaded with ruthenium dioxide as the catalyst. If the rare metals can be recycled with relative ease, the process may have extensive commercial applications. However, if the catalyst in this type of process is lost, the process may become too expensive.

Research must continue to probe the mechanisms of both organic and inorganic reactions to yield better catalysts with reasonable economics. Once the catalysts are identified and understood there is much work left for the engineer to develop the process conditions and control necessary for a successful and productive process. The industrial laboratories have a significant effort in this area.

Advanced Reactor Design. New developments in fluidized bed technology, such as magnetic suspension of the bed, appear promising for long-term applications. The high surface-to-volume ratio of fluidized beds creates the potential for the efficient catalysis of reactions. As reaction mechanisms are better understood, reactor design will become more critical. Already more sophisticated control techniques using computers and newly developed instrumentation have greatly improved reactor design.

Separation Operations

As mentioned earlier, the most energy-intensive step in a typical chemical process occurs when two or more components are separated. Classified on the basis of phases of components in the starting mixture, Table 3.5 shows the diversity in separation operations. Although many of these operations are well suited to their task (and will probably never be replaced), the CPI is full of examples where the separation operation is basically done using the "brute force" method. Often these steps are energy intensive and incomplete. Extra steps are often needed because the separation produces a product of less purity than is required. [For example, in standard ammonia production a methanator is required to rid the process stream of the residual CO and CO₂ left after the bulk of these gases are separated out. More complete extraction of the CO and CO₂ would eliminate the need for a methanator (Burch, Otis and Hale 1979)].

TABLE 3.5. Separation Operations

<u>Liquid-Gas</u>	<u>Gas-Gas</u>	<u>Gas-Solid</u>
Gravity settling	Low-temperature distillation	Gravity settling
Impingement separation	Absorption	Impingement separation
Cyclone separation	Adsorption	Cyclone separation
Foam breaking	Gaseous diffusion	Electromagnetic separation
Drying	Thermal diffusion	Filtration
Boiling	Electromagnetic separation	
Condensation	Chromatographic separation	
	Condensation	
<u>Liquid-Liquid</u>	<u>Liquid-Solid</u>	<u>Solid-Solid</u>
Distillation:	Sedimentation	Size classification
Rectification	Thickening	Screening
Azeotropic	Clarifying	Dense-medium separation
Extractive:	Filtration	Jigging
Molecular	Centrifugation	Tabling
Extraction:	Drying	Magnetic separation
Solvent	Spray drying	Electrostatic separation
Precipitative	Evaporation	Flotation
Dialysis	Crystallization	Sublimation
Electrodialysis	Prilling	Freeze-drying
Thermal diffusion	Graining	
	Leaching	
	Expression	

As new, more sophisticated reaction chemistry becomes the norm, better separation methods will be required to remove expensive catalysts or to separate closely resembling components. These methods must be less expensive, less energy intensive, and of higher quality than past methods. The most promising areas include membrane separation, super critical fluid extraction, and freeze crystallization.

Membrane Separation. A membrane is a thin section of material that acts to separate other materials, yet is permeable to components in solution. The

membrane may be a solid, such as the synthetic polymers used for gas separations and water desalination, or the membrane may be a liquid. In liquid membrane systems, a liquid solution is immobilized on a solid substrate or stabilized by surfactants in an emulsion.

Types of membranes include those that use microfiltration, ultrafiltration, reverse osmosis, dialysis, electrodialysis, gas separation, and coupled transport. These techniques and the materials separated are illustrated in Figure 3.12.

Synthetic polymeric (solid) membranes can discriminate among substances on the basis of several physical properties. In microfiltration, ultrafiltration, reverse osmosis, dialysis, and gas separation, molecules are separated according to their size; in electrodialysis, according to their electric charge; in solvent extraction or coupled transport according to their differing chemical potential in solution. Membranes that are permeable almost exclusively to water are used in reverse osmosis.

Liquid membranes can provide much higher diffusion coefficients than solid membranes; consequently, certain processes become much more industrially attractive. A recent assessment of membrane separation technology sites several examples of potential applications for membranes (Lonsdale 1982):

- the separation of the acid gases, particularly the separation of CO_2 from natural gas streams to upgrade the gas stream and to recover the CO_2 for use in secondary oil recovery
- the recovery of oxygen and nitrogen from air with facilitated-transport membranes. Oxygen-enriched air can be used in synfuels production and nitrogen can be used in ammonia synthesis and other industrial applications.
- the separation of ethanol or other potential substitute liquid fuels from liquors produced by fermentation
- the recovery of heat from industrial drying processes by extracting water vapor

MICROFILTRATION

- retains suspended matter
- passes dissolved substances and water

ULTRAFILTRATION

- retains dissolved matter
- passes some macromolecules, microsolute, ions, and water

REVERSE OSMOSIS

- retains all ions
- passes water

DIALYSIS

- retains dissolved matter
- passes microsolute and water

ELECTRODIALYSIS

- retains nonionic matter
- passes ionic matter

GAS SEPARATION

- retains membrane impermeable gases
- passes membrane permeable gases

COUPLED TRANSPORT

- passes carrier complex ions
- M^+ denotes monovalent metal ion
- H^+ denotes hydrogen

FIGURE 3.12. Types of Membrane Separation Processes

- the concentration and separation of acids, bases, and salts in solution by a form of ion exchange known as Donnan dialysis
- chemical or biochemical conversions in which immobilized catalysts are combined with membrane separators.

In general, the potential for membranes is very good; energy savings can be quite substantial. A good example of the savings is in the chloralkali industry where recent implementation of membranes has yielded a 25% reduction in energy consumption. With the production level of caustic soda in 1981 at 21×10^9 lb, the corresponding energy consumption was approximately 1×10^{14} Btu. Thus, a 25% improvement could save 25 trillion Btu each year. Other potential applications could yield similar savings.

Super Critical Fluid Extraction. When certain substances are operated above their critical temperature, their properties are such that substantial quantities of another substance can be dissolved. Usually, these substances are relatively insoluble at normal temperatures in the liquid or gaseous state. Since the enhanced solubility effect is selective to a degree, a super critical fluid (SCF) can form the basis of a system for separating components of mixtures.

SCF separations are typically carried out at temperatures that are moderate by CPI standards. As a result, they tend to be economical in terms of energy requirements. However, they also tend to be capital intensive because of the high pressures involved.

Many of the presently known applications deal with the food processing industry (e.g., removing extracts from certain foods using super critical CO_2). In the CPI, SCF systems may be used to extract ethanol from the fermented mash. Some estimates indicate that the energy savings of extracting ethanol via SCF systems may be 50% of that required for common distillation.

One barrier to developing SCF technology is a lack of a fundamental engineering data. As more and more data are generated, engineers will be able to develop new processes using the technology.

Freeze Crystallization. In some applications, freezing can be used to assist in separations, resulting in a 75 to 90% reduction of the energy

required by conventional distillation. Two examples of this application are the production of acetic acid and acrylic acid. In this process, one component is solidified and chemically separated from the others. The most well-known applications are in the paper and pulp and food processing industries. Although the basic mechanisms and hardware are understood, further development work is needed to use the concept in specific processes, possibly in combination with other separation methods.

3.4 PETROLEUM REFINING

The petroleum refining industry (SIC 2911) is responsible for processing crude oil into several different products. These products include gasoline, jet fuel, distillate and residual fuel oil, liquefied gases, asphalt, and lubricants. The single most important refinery product is gasoline, which has accounted for roughly 40% (by volume) of U.S. refinery product demand for the last three decades (Gaines and Wolsky 1981). The crude capacity of U.S. refineries as of January 1980 was 18.7 million barrels per stream-day (17.8 million barrels per calendar-day, after adjusting for operating time), or 925 millions tons per year (Gaines and Wolsky 1981).

Petroleum refining is a very energy-intensive process, and the industry is the third largest industrial user of energy. In recent years, the energy used annually in petroleum refining has been roughly 3×10^{15} Btu. Slightly more than half of the energy used in petroleum refining comes from the refinery process streams in the form of refinery gas, oil, liquid petroleum gas (LPG), and coke. Approximately one-third of the energy used in refining is from purchased natural gas, with the remainder being purchased electricity, purchased steam, and a very small contribution from coal and other products (Haynes 1976; Gaines and Wolsky 1981; Lerner et al. 1982). Overall, the energy used to process crude oil represents about 10 to 15% of the total energy available in the crude (Maier et al. 1979; Gaines and Wolsky 1981; Robertson 1982).

The relative amounts of energy used in petroleum refining processes vary among individual refineries due to differences in the types of products produced within the refinery, refinery capacity and age, and the type of processing steps and equipment used. On an aggregated basis, the processing steps of

crude separation, reforming, and cracking are the major consumers of energy in petroleum refining, accounting for over three-fourths of the energy used in refining crude oil. A breakdown of energy use by various refining processes is given in Table 3.6.

The majority of the total U.S. refining capacity is concentrated in large plants with greater than 100,000 barrels per day (bpd) capacity. Table 3.7 gives a breakdown of refining capacity by plant size as of January 1980. This table shows that although the large plants constituted only 19% of the total number of plants, they contributed almost 65% of total refining capacity. A recent estimate puts total capacity in the petroleum refining industry at roughly 18,230,000 bpd in September of 1981. Of this operable capacity, 12.28% was shut down. Total operable capacity was expected to expand roughly 2.5% during 1982, with 20 refinery projects adding 455,000 bpd capacity (Hydrocarbon Processing April 1981). Historically, refining capacity has grown at an average rate of 3% per year since the 1950s.

Oil refining output can be expanded by adding new plants, by expanding the capacity of existing plants, or by recommissioning shut-down units.

TABLE 3.6. Energy Use by Petroleum Refining Process

Process	Percentage of Energy Use	
	Process	Total
Crude Separation	36.4	36.4
Reforming	22.5	58.9
Cracking	18.1	77.0
Hydrogen Treating	8.5	85.5
Alkylation	6.3	91.8
Miscellaneous (lighting, shops, etc.)	5.5	97.3
Hydrogen	2.5	99.8
Isomerization	0.2	100.0

Source: Haynes 1976.

TABLE 3.7. U.S. Refining Capacity by Plant Size in January, 1980

Capacity Measure	Plant Size, 10 ³ bbl/sd			Total
	>10	10-100	>100	
Number of Plants	80	161	56	297
Total Capacity (10 ³ bbl/sd)	446.3	6110.6	12,140.8	18,697.7
Percent of Plants	27	54	19	100
Percent of Capacity	2.4	32.7	64.9	100

bbl/sd = barrels per stream-day, based on actual on-stream time of units.

Source: Gaines and Wolsky 1981.

Expanding existing plants is much more common than constructing new plants. In 1975 and 1976, expansion accounted for 86 and 76%, respectively, of capacity increases, with new plant construction accounting for 10 and 24% of capacity increases (Gaines and Wolsky 1981). This pattern of expanding plants rather than constructing new plants creates a barrier to completely integrating the most energy-efficient processes and equipment in petroleum refineries. Whereas a new plant can be designed from the ground up for maximum energy efficiency, expanding an existing plant must be integrated with the existing processes and equipment, which may preclude maximum energy efficiency.

Oil refining technology is being researched both by oil companies and by support industries specializing in refining equipment and processes. Some refining specific research may also be conducted by universities, but preliminary contacts indicate that this is small compared to research conducted by private firms. Whereas the sample of universities and private firms contacted for this project was small, research did not seem to be oriented toward long-range changes in the basic processes used in petroleum refining.

The oil-refining industry is currently being adversely impacted by the recession in the U.S. and depressed economic conditions in industrial countries worldwide. Petroleum demand in the free world has been declining recently, resulting in the permanent shutdown of 1 million bbl/d of U.S. capacity in

1981, and the idling of another 2 million bbl/d capacity. In the longer range outlook for the 1980s, only moderate growth in the demand for refined petroleum products is forecast, while foreign competition is expected to be increasing. Therefore, the U.S. petroleum refining industry most likely can expect a much lower growth rate in the next decade than it experienced in the 1960s and early 1970s (Chemical Engineering 1982a).

3.4.1 Alternative Industrial Materials Processes

An analysis of the overall energy efficiency of the petroleum refining industry can help in defining whether advanced industrial processes offer potential for saving energy within the industry, and in determining the general areas that offer the most promise for advanced industrial processes. As was previously mentioned, the average energy used in refining crude oil typically represents 10 to 15% of the energy available in the crude. This indicates that the refining process has an efficiency of 85 to 90%. However, it is important to realize that this is an efficiency from a first law of thermodynamics perspective, which treats all units of energy as being equal. A second-law perspective on efficiency is potentially more informative, since the second law of thermodynamics recognizes the work potential of energy, and that the potential for work is lost in all real processes.

The second-law efficiency of petroleum refining is about 9%, indicating that a large portion of available work is being lost (Kenney 1981). Some of this work is lost by using refining processes that have inherent irreversibilities, such as the combustion of fuel in furnaces. Another source of lost work is using large driving forces to operate the process at an economic rate, rather than using infinitesimally small driving forces (such as very low temperature differences) that would provide a more efficient process but one that would take an infinite time.

The low second-law efficiency suggests there may be ways to significantly decrease the amount of energy used in petroleum refining. Even a small improvement in the second-law efficiency could have a large effect on the total energy used in the industry by more effectively using the work potential in crude oil. The main energy users in petroleum refining (separation processes,

reforming, and catalytic cracking) all have fairly low second-law efficiencies, indicating that these areas are potentially fruitful for the development of advanced processes.

The complexity of petroleum refining provides a general barrier to developing and implementing advanced processes. Refineries produce many different products from a wide variety of crude oils, the composition of which may change seasonally or even daily. Although the many processes in refining are tied together with material and energy flows, processes for distinct products may be required to operate semi-independently (Robertson 1982). In addition, because energy quite often flows between processes (waste heat from one process being used to drive another process), an increase in the efficiency of a single process could be partially mitigated by decreased efficiency in connected processes, at least in existing plants.

Several areas of potential for revolutionary processes within the petroleum refining industry have been identified. Some of these areas are fairly specific in terms of applications and the processes they would displace, such as membrane separation. Other areas are more general, either because they potentially apply to many processes or because they have been developed less fully. A common problem with all of the revolutionary processes is that they have not been developed in enough detail to allow reasonable estimates of potential energy savings in the petroleum refining industry. Estimates of energy savings would require (along with industry data) knowing process efficiencies for the revolutionary process, identifying the specific processes that could be replaced or augmented with the revolutionary process, and assessing the effect the revolutionary process would have on the energy consumption of other petroleum refining processes connected by materials or energy flows. This lack of information on the revolutionary processes has led to only qualitative assessments of the energy-saving potential.

Membrane Separation

Membrane separation processes are alternatives to conventional separation techniques such as distillation, stripping, and absorption. The potential use of membranes in petroleum refining is shown schematically in Figure 3.13. Membrane separation works by introducing the components to be separated to a

FIGURE 3.13. Conventional Petroleum Processing Sequence and the Use of Membrane Separation Processes

membrane that (ideally) is permeable to one substance but not to the others in the mixture. The substance that the membrane is permeable toward will diffuse through the membrane and be separated from the other components in the mixture.

Much interest is currently being expressed in membrane separation research, and several membrane separation processes are commercially available, such as reverse osmosis. However, no membranes are available for the separation of organic liquids, which is one of the areas in which membrane separation could have a large impact. These separations in petroleum refining are done through distillation, where large latent heat input required for the separation can give it a very low second-law efficiency. Developing membrane separation techniques to even partially replace distillation to separate organic liquids could potentially save large amounts of energy (Humphrey 1982). Membrane separation is discussed more fully in Section 3.4.2.

Catalysis

Catalysis can be broadly defined as a chemical process in which the reaction rates are subjected to the influences of substances that may or may not change during the reaction (Perry and Chilton 1973). Improvements in catalysts used in processes can improve process yield, can reduce the required reaction temperature, or can do both combined. Either effect tends to increase the efficiency of the process and results in energy savings. Reductions in required reaction temperatures are particularly important, since high reaction temperatures generally lead to large amounts of lost work and low second-law efficiencies for processes.

Advanced catalysts could have an impact on energy use in petroleum refining either by developing new catalyzed processes or by developing improved catalysts for current catalytic processes. Several processes in petroleum refining use catalysts; examples include catalytic cracking and reforming, which are both large energy users. The primary barrier to developing improved catalysts for these processes is a lack of good understanding of how catalysts work. Much effort is expended by industry to develop improved catalysts for processes, but catalysis development could still be termed as much an art as a science; catalysts are generally selected for applications on an empirical basis. When the basic understanding of how catalysts work is improved to the

point that catalysts can be engineered for specific applications, large improvements in the efficiency of many refining processes may be possible.

Quantifying energy-saving potential from advanced catalysts is very speculative; however, historical evidence from catalyst development indicates that the energy savings could be very large. Current catalytic processes used in petroleum refining make oil refineries much more efficient and versatile than they were in previous decades. A documented example from another industry illustrates the gains in process efficiency that have been achieved through catalysis. Reickert (1974) calculated the energy efficiency of the old, non-catalyzed ammonia process as 17%. Development of the catalyzed process currently used increased the energy efficiency to 55%, an improvement of roughly a factor of 3. Whereas improvements of this magnitude are not possible for many petroleum refining processes, significant improvements in process efficiency can be made.

Genetic Engineering

Applied genetic engineering may make possible the development of organisms which, through biological reactions, could partially or totally replace a chemical process in petroleum refining, such as cracking. Reactions could be carried out either in situ, by injecting the organisms into the reservoir, or in a closed system, such as tanks. A closed system would be more capital intensive but would provide a more controlled environment and may be necessary for long-term survival of the organisms. This is a very speculative idea but is potentially feasible. Experiments on using biological organisms to enhance the output of petroleum reservoirs have already been conducted with some success.

A recent development in genetic engineering applications relating to petroleum refining has been patented by Omni Biotechnology Ltd. and involves using micro-organisms in refining tar sands. The organisms were mutated by exposure to high energy radiation and can reportedly recover 93% of the tar in a continuous process conducted at ambient temperatures (Chemical Engineering 1982b).

Extractive Distillation

Extractive distillation involves introducing a chemical agent into the mixture that is to be separated. The chemical agent, or solvent, favorably changes the vapor-liquid equilibrium of the mixture, typically through some sort of reversible chemical reaction or bonding. The modified vapor-liquid equilibrium of the mixture can allow improved separation of the components with less energy input. Extractive distillation is used to some extent in the petroleum refining industry now, not for energy conservation purposes, but because it can produce very pure products and perform difficult separations.

The need to separate the solvent from the end product adds an additional step to extractive distillation that is not found in simple distillation. Consequently, extractive distillation tends to be a more complicated and capital-intensive process than simple distillation. Depending on the type of solvent used, the extra separation step in extractive distillation can actually make it more energy intensive than simple distillation. This characteristic has tended to limit the use of extractive distillation in petroleum refining to fairly difficult separations. With energy costs now being a large portion of refinery operating costs, extractive distillation could become an attractive prospect for separations purely on the basis of energy savings if appropriate solvents can be identified. The largest technical barrier is the need to identify agents that can be used in energy-efficient extractive distillation processes for each separation process, since each process will be unique and will require a unique agent.

Replacing Combustion Processes

Thermodynamic analyses have shown that the combustion of fuel to provide process heat contributes greatly to the lost work and low second-law efficiency of petroleum refining. These fuels are converted into energy in furnaces where the second-law conversion efficiency is about 30%. The work lost in the combustion process is due both to irreversibilities of combustion and the large temperature driving forces used in furnaces (Kenney 1981).

The overall goal of replacing combustion processes is to improve refining efficiency by reducing the amount of fuel burned. On a simple level, this can be (and is) done by using waste heat to offset the need to burn fuel. Beyond

this simple approach, two possibilities could achieve this goal. Alternative sources of process energy could be found, or an alternative to the combustion process could be developed for using the energy in the fuel. Several process energy alternatives are technically feasible, such as using solar or geothermal energy for process heat, but these options are generally not economically attractive for most refineries at today's fuel costs. Developing an alternative chemical reaction to combustion to more effectively use the energy from fuel may be feasible and could have a large impact on the amount of energy used in petroleum refining. One example of a way to release the energy in fuel without combustion is through a fuel cell, where chemical energy is directly converted to electrical energy. Other options may also be feasible, but no specific processes for use in petroleum refining have been proposed either in the literature reviewed or by experts contacted.

3.4.2 Investigation of Selected Processes

Of the candidate revolutionary processes identified in the previous section, one process appears particularly promising in terms of its energy conservation potential and technical feasibility. This process is membrane separation and will be discussed further in this section.

Membrane Separation

Membrane separation processes use differences in the rate of diffusion across a semipermeable barrier to separate substances. Ideally, the mixture of substances is introduced to a membrane that is permeable to one substance in the mixture that diffuses across the membrane and is separated from the other components in the mixture. Membrane separations are possible for gas-gas, liquid-gas, or liquid-liquid separations, all of which are used in petroleum refining. Currently, some membrane separation processes are in commercial use today, such as reverse osmosis for separating water from a mixture, and the Monsanto Prism (R) membrane system for separating hydrogen gas from purge streams. The membrane separation processes that are probably the farthest from commercialization are for liquid-liquid separations of organic fluids, and it is these processes that are discussed in this section.

Using a membrane separation process to separate organic liquids could replace the distillation processes currently used in petroleum refining. The

principal advantage a membrane separation process could have over distillation is the potentially large savings in process energy. Distillation has inherently low second-law efficiencies due to the large amount of energy consumed in going through a phase change from liquid to vapor. Membrane separation does not involve a phase change to separate components of a mixture and can have a much higher efficiency than distillation. As an example, the energy required and second-law efficiency for desalinating sea water by evaporation and by reverse osmosis are shown in Table 3.8. The second-law efficiency of the membrane separation process is nearly 4.5 times greater than that of the distillation process.

The amount of energy that potentially could be saved in the petroleum refining industry by developing advanced membrane processes for separating organic liquids is difficult to quantify for several reasons. A primary problem is that the ultimate separation efficiencies of membrane processes are not known. Even membrane processes that can currently be considered commercialized, such as reverse osmosis, could potentially have their efficiencies substantially improved (Ford et al. 1975). Another difficulty in quantifying energy savings is identifying the exact amount that membrane separation could replace distillation in petroleum refining. Finally, energy flows in petroleum refining are connected across processes, with waste heat from one process often being used in another process. The flow of energy between processes would require a fairly detailed analysis of the refining operation as a whole to assess the impact of membrane separation on the overall energy use in petroleum refining.

TABLE 3.8. Comparative Energy Use for Desalinating Sea Water

	<u>Fuel Energy per Unit of Fresh Water (KJ/kg)</u>	<u>Second-Law Efficiency</u>
Minimum Separative Work to Desalinate 50% of the Water	3.5	1.0
Separation by Distillation	280	0.013
Separation by Reverse Osmosis	60	0.058

Source: Ford et al. 1975.

Given the problems in quantifying energy savings discussed above, only a very crude estimate of potential savings from membrane separation is possible. This rough estimate can be developed as follows. Allowing for a total industry energy consumption of 3×10^{15} Btu per year (as discussed in the introduction) and using the energy breakdown given in Table 3.8, the annual amount of energy used for crude separation is about 1.1×10^{15} Btu. Table 3.8 shows that the energy used for reverse osmosis desalination of sea water is only 21% of the energy required for the distillation process. If membrane separation of organic fluids is assumed to also use 21% of the energy for distillation, and if membrane separation could completely replace distillation in petroleum refining, then about 8.7×10^{14} Btu per year could be saved. These energy savings represent 29% of the total energy used in all petroleum refining processes.

There are several technical barriers for implementing membrane separation processes for organic liquids. Perhaps the largest barrier is membrane development. A unique membrane would be required for each type of component separation performed. Currently, no membranes are available for commercial separation of organic liquids. Requiring a membrane for each separation would greatly increase the amount of process equipment needed in refining and could create problems with integrating the equipment into existing refineries. Also, long-term durability of the membrane is a concern even for systems that are currently commercially available and will probably be a problem to overcome for membranes to separate organic liquids. Other problems include low rates of permeation and low separation factors, particularly for some isomers and structurally similar compounds (Humphrey 1982).

Generally, membrane separation of organic fluids in petroleum refining appears to be some ways from being commercially applied. Given the generally conservative attitude of the refining industry, the problem of adapting radically different processes into existing refineries, and the pattern of expanding refineries rather than constructing new ones, it would seem to be an even longer time before membrane separation could have a major impact on the amount of energy used in petroleum refining.

3.5 PULP AND PAPER

Estimates of the fuel and energy used in the U.S. pulp, paper, and paperboard industry, as provided by the Energy Materials Department of the American Paper Institute (1982), are given in Table 3.9. The total energy used in 1981 for a sample of 91.8% of the industry, was 2.15 quads.

As shown in the table, an estimated 50.1% of the total energy required for the manufacture of pulp, paper, and paperboard is generated from renewable process residues including spent pulping liquor, bark, and wood residues. This represents an improvement over the 40.5% of the total energy requirements being generated from the same sources for 1972. The total savings in purchased energy between the 1972 and 1981 is the equivalent of approximately 31 million barrels of oil.

The trend in fossil fuel and purchased energy consumption per ton of paper products as well as the energy self-sufficiency trend in the industry is shown in Figure 3.14. The trends show a substantial progress in energy conservation in the U.S. paper industry. The API estimates that the paper industry has reduced its use of fossil fuel and purchased energy per ton of output by 30.4% between 1972 and 1981. This trend and the increase in energy self-sufficiency are shown in Figure 3.15. The actually reported improvement was 24.8%, but an adjustment was necessary to account for operational changes between 1972 and 1981. The adjustment was made to include operational changes in capacity utilization rate, fuel mix, and energy use for environmental control. The evidence of energy-efficiency improvement is provided by the fact that while paper and board output increased by almost 18%, the purchased energy requirements were reduced by over 11% and the consumption of oil was reduced by 40%.

There has been a continuous trend of increasing cost of purchased fuels and electric energy as a percentage of the value of the shipments, as shown in Figure 3.16. The cost has increased from 7.0% of the value of the shipments in 1972 to 13.8% in 1981.

The major fuel-consuming processes in papermaking, together with estimates of energy consumption, are given in Table 3.10. The most energy-intensive areas in papermaking are seen to be pulping, refining, and the paper machine.

TABLE 3.9. U.S. Pulp, Paper and Paperboard Industry Estimated Fuel and Energy Use in 1981(a)

<u>Source</u>	<u>Units</u>	<u>Estimated Use</u>	<u>Billion Btu</u>	<u>Percent of Total^(b)</u>
Purchased Electricity	MMkWh	41,324.8	140,528.3	6.5
Purchased Steam	MM lbs	13,111.5	15,246.3	0.7
Coal	M tons	9,995.8	244,141.9	11.2
Residual Fuel Oil	M 42 gal bbl	42,050.4	264,602.2	12.2
Distillate Fuel Oil	M 42 gal bbl	1,326.8	7,924.8	0.4
Liquid Propane Gas	M gal	21,666.7	1,998.2	0.1
Natural Gas	mmcf	396,270.0	405,026.1	18.7
Other Purchased Energy	--	--	3,062.3	0.1
Energy Sold	--	--	(-21,880.8)	
<u>Total Fossil Fuel and Purchased Energy</u>			<u>1,060,649.3</u>	<u>49.9</u>
Hogged Fuel (50% moisture content)	M tons	17,3909.5	145,414.4	6.7
Bark (50% moisture content)	M tons	12,493.0	108,644.9	5.0
Spent Liquor (solids)	M tons	66,277.6	816,001.7	37.6
Self-Generated Hydroelectric Power	MMkWh	2,777.8	9,445.9	0.4
Other Self-Generated Energy	--	--	8,996.6	0.4
<u>Total Self-Generated and Residue Fuels</u>	--	--	<u>1,088,503.5</u>	<u>50.1</u>
<u>Total Energy</u>	--	--	<u>2,149,152.8</u>	<u>100.0</u>

(a) Based on a sample of 91.8% of total dried pulp, paper and paperboard for 1981.

(b) Determined by using "Total Energy" + "Energy Sold" as a denominator.

Trillion BTU's
Consumed

FIGURE 3.14. Pulp, Paper and Paperboard Industry Changing Fuel Mix, 1972-1981

FIGURE 3.15. U.S. Paper Industry

March 1983

Includes electric energy, fuel oil, coal, natural gas and other fossil fuels. Based on discussions with the Bureau of the Census, it is unlikely that the reported data includes significant quantities of wood based fuels, such as bark, hogged fuel, spent pulping liquor.

Source: Survey of Manufacturers, Bureau of the Census.
Cost of Purchased Fuels & Electric Energy estimated by API for 1972, 1973, 1977, 1978, 1979, 1980, 1981.

E Estimated P Preliminary (Source: American Paper Institute) March, 1982

FIGURE 3.16. Pulp, Paper and Paperboard Industry Cost of Purchased Fuels and Electric Energy(a) as a Percentage of Value of Shipments, 1972-1981 (millions of dollars)

TABLE 3.10. Major Energy Consuming Processes in Papermaking

Process Step	Electricity (kWhr/ton)	Other (Btu/ton)	Comments
Debarking	Small	--	
Chipping	Small	--	
Pulping - Groundwood	1000 - 1700	--	Electrical energy includes refining
- Sulphate	50 - 100	$3 - 3.5 \times 10^6$	
- NSSC	200 - 500	$1.8 - 2 \times 10^6$	Electrical energy includes refining
- Sulphite	50 - 100	$4 - 5 \times 10^6$	
Washing	30 - 50	0.5×10^6	
Refining	200 - 400	--	
Bleaching	80 - 120	$1 - 3 \times 10^6$	Large quantities of warm water also required
Paper Machine	300 - 400	$5 - 9 \times 10^6$	
Recovery - Evaporator	Small	$2.5 - 3 \times 10^6$	
- Furnace	Small	$18 - 20 \times 10^6$	Net $10 - 12 \times 10^6$ Btu/ton produced as steam
- Lime Kiln	Small	2×10^6	Optimum operating conditions save 10%
Power Plant Operation	Small	$1 - 1.5 \times 10^6$	Auxiliaries and soot blowing
Space Heating	--	$0 - 2 \times 10^6$	Depends on season and location

Source: Thermo Electron Corporation 1976.

From data typical of an integrated Kraft mill, the areas of major energy consumption are as follows:

- In the digester, about 2300 Btu per pound of finished paper are put in. Of this, 1215 Btu per pound are vented in the blow tank as dirty steam.
- In the multiple-effect evaporators used to concentrate the black liquor stream, 2030 Btu (3000°F steam) per pound of finished paper are required.
- In the dryer section, 3500 Btu (250°F) per pound of finished paper are consumed. Most of the energy (2650 Btu) is contained in the resulting mixture of air and water vapor at 240°F.

The pulp and paper industry is a technologically mature industry. It has been said that the basic process of making paper has not been changed much since it was conceived in China in 105 AD by Tsai Lin (BNL 1978). In his process, Mr. Lin macerated mulberry wood into a pulp, laid it on a screen, and set it out to dry in the sun. Of the more modern paper mills, the first groundwood mill and the first chemical woodpulp mills for both the alkaline and acid processes were started between 1852 and 1874. The current conventional pulp and paper processing sequence is shown in Figure 3.17.

Technical progress in the manufacture of pulp and paper products includes modifications of the processes to accommodate a range of wood species; refinements in techniques of forestry, logging, barking, chipping, digesting, washing the pulp, and bleaching. The improvements in papermaking machines or in industry practice have been mostly evolutionary. New pulping methods have been developed, whereas some methods, such as soda pulping, have almost become obsolete. Others, like sulfite pulping, opened the way for Kraft pulping. Some paper mills still use paper machines made in 1900 concurrently with newly purchased machines that are faster, quieter, better engineered, and computer controlled.

The pulp and paper industry is almost universally regarded as very slow to change its production practices and processes. Reasons given include the capital intensiveness of the industry and the high cost of new facilities.

FIGURE 3.17. Conventional Pulp and Paper Processing Sequence

Expensive equipment often is used long after more efficient replacement equipment becomes available. Technological improvements are evolutionary and implementation is taken through a series of small steps. Most frequently, improvements are represented by retrofit technologies that do not require fixed-capital expenditures and expensive downtime in the production line.

The pulp and paper industry is heavily geared towards mass production. R&D has therefore been focused in improving present production technology. This, together with process development and process improvement, takes a major share of the R&D since even modest incremental improvements can lead to enormous returns to the industry.

In 1981, the industry spent approximately 0.9% of its sales dollars for R&D (Business Week July 1982). This compares with 0.6% of its sales dollars in 1975 (Chiogiogi 1979). Of the 1975 R&D dollars, over 80% of the outlay was attributable to a few large companies. No distribution was given for the 1981 expenditures. However, of the money spent in R&D in 1975, 33% went to new products, 26% was directed toward processes, and 41% went to existing products.

In addition to the research conducted at company-owned laboratories, paper-related R&D is also conducted under cooperative industry funding. Among the centers performing research are the Forest Service, the Institute of Paper Chemistry, Miami University in Ohio, North Carolina State University, the SUNY College of Environmental Science and Forestry in Syracuse, New York, the University of Maine at Orono, the University of Washington, Washington State University, and Western Michigan University.

An assessment of the financial health of the paper industry is reported in the "Technology and Business News" section of the May 1982 issue of TAPPI. Performance of the paper industry is seen to be closely linked to the economy. Production of paper and paperboard in 1981 was 1.2% above the 1980 level. This growth rate is almost the same as the growth in real gross national product. The quarterly patterns in paper and real GNP were also similar for the first two quarters of 1982. Production remained low in January 1982 but strengthened in February, as did the real GNP.

The inventory situation in paper and paperboard is presently the same as in all of industry. Consequently, response to general business trends are expected to be sensitive.

3.5.1 Alternative Industrial Materials Processes

Many ideas on using technologies that will promote more efficient energy use have been generated in this industry. Most of these ideas are evolutionary, involving incremental improvements in existing methods. The breadth of these ideas can be seen in Table 3.11, which provides a list of many of the energy efficiency improvements that have been proposed. These R&D opportunities represent a compilation of ideas posed by experts in industry, academia, and national laboratories. Two criteria were used to select the R&D areas presented on the table: 1) research is still in the laboratory bench-scale, and 2) research is initiated or conducted in a foreign country, in which case the technology may not be easily transferrable to U.S.-based companies. The R&D opportunities listed in the table are grouped according to specific processes that are representative of pulp and paper production.

The energy conservation R&D areas that are receiving the greatest amount of attention by the industry involve improving the Kraft recovery boiler and improving the handling of black liquor. The recovery boiler presents a limiting factor to paper production because of its present recovery capacity. In addition, it constitutes a major capital investment at \$85M per boiler. Alternative technologies to the presently used Tomlinson boiler are of major interest to the industry. The improved boiler will have as a requirement separate oxidation and reduction components to eliminate the hazards of smelt-water explosion.

The improved drying, handling, and firing of black liquor is also of major interest to the industry. Recovery boilers typically fire 65% solids in black liquor; a capability for firing 75% solids would add 6,000,000 tons per year of integrated mill capacity without incurring the associated capital expense, which is approximately \$6 billion dollars (\$333 million/1000 tons per day capacity).

TABLE 3.11. Pulp and Paper Industry R&D Needs and Opportunities Identified in Literature

		- Planting - Gathering - Debarking - Chipping	- Pulp - Bleaching - Evaporation - Calcining (Lime)	- Forming - Evaporation - Finishing		- Cutting - Printing	- Generic; Waste and Heat Recovery
1. Whole tree chipping	1. Thermomechanical pulping	1. High consistency paper forming process	1. Comparison study of alternative available technologies	1. Bark and wood waste fuel preparation			
2. Bark separation from chips	2. Closed water system for pulp washing	2. Dry paper forming process	2. Solventless systems in printing	2. Advanced air/fuel ratio controls			
3. Improved peat control	3. Vapor recompression evaporation for concentrating spent liquor	3. Advanced refiner systems for lower-grade fibers		3. Heat recovery from paper dryers using heat wheels			
4. Biological genetic improvements in trees	4. Higher efficiency in lime kilns	4. More use of secondary fibers for fiber conservation		4. Utilization of waste materials			
5. Whole tree utilization	5. Vapor phase bleaching	5. Twin wire formers		5. Corrosion-resistant economizers			
	6. Pulp fiber characterization using automatic imagery pattern recognition system	6. Closed water system		6. Hot water from flue gas scrubbing			
	7. Automatic control bleaching	7. Extended nip press		7. Fluidized bed			
	8. Automatic control digester	8. Paper pressing		8. New recovery technology			
	9. Automatic control recovery boiler	9. Paper drying using mach air nozzle		9. Clean burning bark burners			
	10. Use of hot water from flue gas scrubbing to eliminate steam usage in the bleach plant	10. Microwave drying		10. Solid waste disposal			
	11. Waste paper characterization	11. Mechanical dewatering		11. Radiant recuperator			
	12. Batch-digester heat reuse	12. Electromagnetic displacement		12. Reduce water to recovery boiler			
	13. Waste paper recycling	13. Fluid displacement		13. Membrane technology for air enrichment			
	14. Pulp washing	14. Physical displacement		14. Improved low temperature heat exchangers			
		15. High temperature forming		15. Low-level heat utilization			
		16. Increased end product moisture		16. Heat recovery from existing dryer			
		17. Lower specification for paper products		17. Improved paper machine hood economizers			
		18. Fluidized bed drying					
		19. Fundamentals of fiber solvent interaction					
		20. Fundamentals of fiber-fiber bonding					

TABLE 3.11. (contd)

- Planting - Gathering - Debarking - Chipping	- Pulp - Bleaching - Evaporation - Calcining (Lime)	- Forming - Finishing		- Cutting - Printing	- Generic; Waste and Heat Recovery
	15. Hydrolysis	21. Higher feedstock temperatures			18. Conserving hood waste heat via heat pumps
	16. Pulp pressing	22. Clay coating			19. Converting waste heat in low temperature water to higher temperature water via heat pump
	17. Freeze crystallization of black liquor	23. Release coatings			20. Investigation of feasibility of bark drying for heat
	18. Alternative fuels for lime kilns	24. New felt designs to reduce energy cost for vacuum pumps			21. New recovery technology
	19. Plasma technology				22. Solid waste (sludge) utilization
	20. Electrochemical regeneration using reducing power of black liquor				23. Solid waste disposal
	21. New lime producing technology				24. Non-biological effluent treatment
	22. Chemistry of causticization				25. Gasifier for transforming wood chips to usable engine fuel
	23. Oxygen pulping				
	24. Press drying system to reduce beating of hardwood pulp				
	25. Oxygen bleaching				
	26. Ozone treatment of Kraft mill effluents				
	27. Energy recovery from black liquor systems				
	28. Preparation of municipal refuse for burning in existing pulp mill bark boiler				
	29. Utilization of steam available from TMP				
	30. Improved Kraft chemical recovery				
	31. Spent liquor fuel preparation				

Far less attention is being given to revolutionary processes. Some of the comments received from pulp and paper experts in telephone conversations may clarify reasons for this:

"Industry is capital intensive and business oriented and cannot accept things that are revolutionary."

"...the U.S. Industry is in a competitive position that is extremely favorable...and will probably stay that way for the next 30 years."

"...paper can be made anywhere in the U.S., shipped to Sweden and still be sold cheaper than Swedish-made paper..."

"...industry has not felt any significant competition...it doesn't see a need to pursue revolutionary ideas..."

"...innovations in the processes seem to be initiated abroad, mainly in Sweden and Finland..."

"...innovations result from competition among suppliers of equipment to the industry..."

The potential for revolutionary change may nonetheless be significant. In an article published in the TAPPI Journal of July 1982, D. G. Harvey indicated that:

"The future of the paper industry may well belong to those who have the creativity and willingness to accept risk not normally found in a well-established industry."

He feels that major process innovation opportunities lie in the answers to the following questions:

- How can black liquor be processed to yield something more valuable than its fuel value?
- Are there alternatives to sulfite digestion for cellulose separation? Can biological species be developed to accomplish separation?

- Do the copious quantities of sludge produced represent a viable source of energy or feedstock?
- Is the water-based papermaking process the only or best means of forming quality sheet?

In his address as the 1982 TAPPI Gold Medalist (TAPPI April 1982), A. H. Nissan also discussed some of the potential for major process innovation. He mentioned a pulp that he calls the "9-90-90" pulp that will revolutionize the industry. This pulp will possess the most desirable pulp characteristics needed for paper production. These characteristics are as follows:

- a 9-mm breaking length, which is normally achieved through chemical pulping
- a permanent brightness of 90%, which is normally achieved through bleaching
- 90% yield of a mechanical pulp.

He accepted the fact that a process that will produce this pulp presents a difficult, but not impossible, challenge to the industry (TAPPI 1982).

The candidate revolutionary pulp and paper processes that were identified in this study are described below. Because the industry does not have incentive to pursue long-term revolutionary changes, minimal research is under way in all of the processes discussed.

Dry Forming of Paper

Paper production is water intensive and was among the top three users of water in 1973 (Hersh 1981). Good bonding of the cellulose fibers requires water. The water facilitates stitching of cellulose molecules into a bonded network in the dryer section. A dry forming process, sketched in Figure 3.18, will eliminate the energy-intensive drying process needed to evaporate the water from the wet-formed sheets of paper. This process will be discussed more thoroughly in Section 3.5.2.

FIGURE 3.18. Dry Forming

Pulping Through Solvent Extraction of Lignin

A new process using solvent extraction could provide a significant alternative to the alkaline Kraft pulping process, which accounts for 8 to 10% of the process energy. A solvent or mixture of solvents can be used to totally extract the lignin from the wood mass or to expand the lignin cellulose matrix for more rapid digestion.

Lignin Biodegradation

Lignin and hemicellulose can be degraded by micro-organisms to obtain pure fractions of cellulose from wood. Lignin depolymerization by enzymatic action can be used as an alternative to conventional pulping methods. Methods of pulping by biodegradation should result in lower energy use by reducing mechanical reduction requirements and by eliminating the digester.

Autocaustization of Pulping Chemicals

The lime kiln uses 13 to 15 million Btu per ton of paper product when theoretically it should use only 8 million Btu per ton. Provision for auto-caustization of the input chemicals to the digester, possibly in the recovery boiler, could lead to elimination of the lime kiln, thereby conserving 5 to 7 million Btu per ton of paper product.

Lower Energy Chemistry in Pulping

The chemical reaction to extract lignin from the wood mass possibly could be carried out at a lower rate of energy consumption. Inducing the chemical reaction with lasers could drive the reaction through a lower pressure and temperature path that will result in less energy than presently used reaction paths.

Carbothermic Reduction of Sodium Carbonate

Sodium hydroxide and sodium sulfide are currently used in the Kraft process to remove the lignin from wood. Spent liquor (black liquor) is usually burned to recover both heat and process chemicals. In the chemical recovery process, sodium is first reacted to form a carbonate and then reacted with slaked lime to form sodium hydroxide. Direct reduction of sodium carbonate would eliminate the need for the lime kiln and lime slaking.

Alternative Debarking Methods

Lightning has been observed to strip the bark cleanly from trees. This suggests that a capacitive discharge method is an alternative to presently used debarking techniques. Other alternative energy forms that could be exploited include sonic and microwave energies.

By-Product Recovery

The pulp and paper industry creates large volumes of waste products with substantial organic content. Waste streams from both groundwood and Kraft processes have high fiber content. As such, they represent a potential feed-stock for reactions such as the enzymatic hydrolysis of both cellulose and hemicellulose. If this type of application is successful, it would provide for another product from the mill and simultaneously reduce the quantity of waste for disposal. Also, purchased energy might be reduced as a result of an alternative fuel by-product.

Lignin, because it contains biphenyl and polyaromatic groups, can be an important source of aromatic chemicals, which are currently made from nonrenewable petroleum derivatives. A variety of processes can be used to degrade lignin. Some important processes and their products are summarized as follows:

- hydrogenation phenol, creosols, substituted phenolic compounds
- alkali fusion phenolic acids
- pyrolysis - acetic acid, phenol, substituted phenolic compounds, carbon monoxide and methane
- fast thermolysis - acetylene, ethylene
- hydrolysis - phenol, substituted phenolic compounds
- oxidative and miscellaneous uses - dimethyl sulfide, methyl mercaptan.

Many useful chemicals can be synthesized from these products. Some examples include bisphenol A and epoxy resins from phenol; ammonia, urea, methanol and formaldehyde from hydrogen and carbon monoxide; and plastic and resin from

unsaturated hydrocarbons. Research in the areas of degrading processes and product synthesis is needed to make producing chemicals from lignin economically feasible.

3.5.2 Investigation of Selected Processes

Of the candidate revolutionary processes identified in the previous section, one process appears particularly promising for energy-saving potential and technical feasibility. This process is the dry forming of paper and will be discussed in more detail in this section.

Dry Forming of Paper

Fibers held together by interweaving or felting and by bonding among fibers make up the structure of a paper or sheet. Mechanical felting makes a relatively small contribution to the strength characteristics of the sheet. It is the unique ability of cellulose vegetable fibers to form bonds between individual fibers that is used in paper sheet formation and has the greatest contribution to paper strength characteristics. The formation of bonds among cellulose fibers in water suspension was recognized in ancient times. The current theory of bonding is that during drying, the swollen, flexible fibers are drawn together by surface tension forces between fibers and the residual water. Once fiber-to-fiber contacts are established, hydrogen bonding occurs between the hydroxyl groups of adjacent polysaccharide surfaces. The factors that contribute to the final structure of the paper sheet include the type of fiber, mechanical treatment of the fiber, the sheet-forming process, and the pressing, drying and finishing operation.

A waterless papermaking process will have to be based on the dry bonding of fibers without the use of additives and where conventional hydrogen bonding is not a major factor. An inventor from New Zealand claims to have perfected a waterless papermaking process that has apparently been successfully applied to the use of recycled waste paper and agricultural waste such as straw and animal fibers. However, the details of the process have not been disclosed and the operability of the overall system on an industry scale has not been demonstrated. A schematic drawing of how dry forming would tie into the conventional processing sequence was shown in Figure 3.18.

Direct evaporation in the dryer section of the paper machine consumes about 3 to 5×10^6 Btu per ton just to remove the water. Taking into account the energy required to heat the air used in water-vapor removal, the combined energy consumption ranges from 6×10^6 Btu per ton. Based upon the production volume for 1981, this translates to an overall savings of approximately 0.35 quads per year. Paper formation using a dry process will have the potential to save this much energy.

The conditions under which dry bonding of cellulosic fibers can occur are not currently known. Lack of this understanding impedes development of a dry-forming process that can capitalize on conditions that will enhance dry bonding. The technology base R&D activity is needed to enhance the understanding of cellulosic fiber bonding. The present theory of water-based fiber bonding will have to be reviewed in detail and developed to a point where other mechanisms of fiber bonding can be postulated. Possible dry bonding mechanisms can be theorized and verified in the laboratory.

In the definition of possible dry-bonding mechanisms, investigations will have to include basic material and surface sciences. Process variables and the corresponding microscopic characteristics of the fiber bonds affected by the variables will have to be determined. After the fundamental bonding chemistry is understood at the microscopic level, improved macroscopic bonding concepts can be formulated. Experimental measurements will verify and modify the bonding concepts.

A corollary problem to dry forming is dry fiberizing and cleaning. A process to produce dry, clean fibers that will be used in paper formation will also have to be developed. The process should be able to produce fibers at the quantity needed for mass paper production.

From the laboratory bench scale, the dry forming process will have to be scaled up to production. The set of process variables needed for scaling up will have to be researched further before the process can be implemented at the production level. Also, a new paper machine may have to be developed.

3.6 FOOD AND KINDRED PRODUCTS

The food and kindred product industry (SIC-20) includes facilities that manufacture or process foods and beverages for human consumption and certain related products such as manufactured ice and prepared feeds for animals and fowls. This industry uses about 960 trillion Btu of energy annually and ranks sixth in energy consumption for all industries. The total energy used in the food industry represents about 7% of the total energy consumed by all U.S. industries. Approximately 51% of the energy used in the food industry is supplied by natural gas; this is followed by fuel oil at 22%, electricity at 16%, and coal and coke at 11%. The total annual cost of purchased fuels and electric energy for the industry was about \$2.5 billion in 1977 (U.S. Department of Commerce 1980). This is a diverse industry with over 28,000 individual facilities with 56% of them having fewer than 20 employees.

The energy consumption of the top ten industries in this industrial group is shown in Table 3.12. As shown by the table, wet corn milling (SIC-2046) consumed the most total energy, accounting for almost 85 trillion Btu annually. Sugar-beet processing (SIC-2063) ranks second with an annual consumption of

TABLE 3.12. Energy Consumption in the Food and Kindred Products Industry (SIC-20)

<u>Rank</u>	<u>SIC No.</u>	<u>Industry</u>	<u>Total Energy Consumption (10¹² Btu) 1977</u>
1	2046	Wet corn milling	84.4
2	2063	Beet sugar	75.1
3	2011	Meat packing plants	64.4
4	2082	Malt beverages	50.1
5	2033	Canned fruits and vegetables	47.3
6	2051	Bread, cake, related products	45.8
7	2075	Soybean oil mills	45.3
8	2026	Fluid milk	34.7
9	2037	Frozen fruits and vegetables	33.4
10	2062	Cane sugar refining	32.5

75 trillion Btu. The top ten industries consume about 513 trillion Btu annually or about 53% of the total consumed by the food and kindred products industry.

The cost of energy compared to the total value of shipments or value added will vary considerably among component industries and among individual plants within a component industry. In 1977, the cost of purchased fuels and electric energy averaged 1.3% of the value of shipments or 4.5% of the value added by manufacturing for the food and kindred products industry (U.S. Department of Commerce 1980). Although more recent industrial statistics are not available, energy costs in 1982 are expected to represent less than 10% of the value added by manufacturing.

Research for the food industry is conducted by the federal government (USDA), the state agricultural experiment stations (including the land-grant universities), private industry and other research institutions. The Office of Technology Assessment (OTA) (1981) has concluded that "the lack of well-defined and agreed-upon national goals for U.S. food and agriculture is a major deterrent in formulating broad food and agricultural policy at the national levels." At least 10 federal agencies other than USDA fund or conduct some kind of food and agricultural research. These include the Departments of Commerce, Defense, Energy, Health and Human Services, Interior, and State Agency for International Development; the Environmental Protection Agency; the National Science Foundation; and the Tennessee Valley Authority (OTA 1981). These agencies fund or conduct research directed toward energy conservation in food processing and related to the primary objective of the agency. As expected, DOE is the primary federal agency involved in funding energy conservation research. Private industry research is conducted in areas that are of major concern to the firm, with the primary concern being profitability. In contrast to the cost of energy, raw material costs represent a large portion (approximately 70%) of the total costs for the food and kindred products industry.

The industry is generally conservative when it comes to investing in new equipment. They require proven technology since they cannot afford to have the process shut down. Also, because of the importance of raw material costs

in the conversion to the final product, new processes that increase product recovery but use more energy may be favored over energy conservation technologies.

Although the economy of the food industry is generally stable, it is also a very competitive industry and very little excess capital is available for investments in improvements and expansions except for the most promising ones.

3.6.1 Alternative Industrial Materials Processes

The food and kindred products industry is a diverse sector containing many component industries and many different processes within each industry. The leading energy-consuming industry in this group is wet corn milling, but it still accounts for less than 10% of the energy used by the total food industry. Within wet corn milling, the largest energy-consuming step is for steepwater evaporation, which accounts for roughly 20% of the energy consumed. Thus, any one single energy conservation technology will not have a large impact on the food industry as a whole and many technologies will be required to significantly reduce energy consumption by the industry. Many different energy-conserving technologies that may be considered revolutionary have been suggested by researchers in the field; these are addressed below. The order in which they are discussed does not imply ranking. Although this list is expected to cover the major areas of advanced alternative processes, it should not be considered to be all inclusive.

Modified High Fructose Corn Syrup Process

The production of high fructose corn syrup (HFSC) by the process of corn wet milling requires large volumes of water for the steeping and milling operations. The water, incorporated into various process streams, requires extensive dewatering, drying, and evaporation, resulting in an energy-intensive process. To reduce the overall energy requirements of HFCS production, an alternative process is being explored that combines initial dry milling of corn with subsequent solvent extraction of protein and conversion of starch to syrup. This scheme is outlined in Figure 3.19. Based on laboratory studies of the alternative process, the water removal load is less than half of that

FIGURE 3.19. Modified High Fructose Corn Syrup Process

for wet milling, and a full-scale plant using the alternative technology should require 30% less energy than a corresponding wet milling facility (Russell and Tsao 1981).

Genetic Engineering

Genetic engineering is expected to play a major role in advances in the food processing industry. The category of genetic engineering is very broad and many developments will be directed at goals other than energy conservation (e.g., new sources of foods and food additives). However, in many cases genetic engineering will be applied in the food industry and will directly or indirectly be related to energy conservation. Raw materials could be modified genetically so that they contain less moisture at harvest and thereby would require less energy for drying while still maintaining other desired characteristics. Genetically engineered enzymes could be used to control the metabolic rate of fruits and vegetables to aid preservation. Genetic engineering could advance development of the single-cell protein and amino-acid industries, which would replace more energy-intensive industries. Enzymes such as those used to hydrolyze starch could be improved so that product yield and quality are improved, thereby indirectly reducing energy requirements. The technological breakthrough required in genetic engineering appears to be largely at the basic rather than applied level. For example, once the techniques of genetic engineering are perfected for production of enzymes, applications in the food industry will follow.

Alternatives to Thermal and Refrigeration Processes for Food Preservation

The potential concepts to be developed include irradiation (high and low level), grain fumigation processes, growth regulators to reduce decay and increase shelf life, ultra high temperature rapid sterilization, and development and application techniques for immobilized antibodies to selectively adsorb and remove undesirable bacterial agents. Research would be needed on dosages, time effect of preservation process, application techniques and study of adverse effects (Centec Corporation 1981). Each of these techniques has been investigated to some extent, but additional research is required to perfect the techniques and to develop commercial systems. Some of these processes

may alter the product properties or may be perceived by the consumer to have been altered. Therefore, those developing these energy conservation technologies will need to be aware of these market considerations.

Some processes may follow the model of sterile acceptable milk. Direct ultra high temperature processing was used to produce a product that can sustain shelf lives of 8 to 9 weeks at room temperature (68°F/20°C). The process also preserves the quality of the product with no significant degradation in its taste. The energy conservation potential of this option was estimated to be equivalent to 185 million barrels of oil (1.1 quads) between 1983 and 2000 (University of Maryland 1980).

Preservation of Fresh Solid Foods by Gas Exchange

The gas-exchange process is based on principles employed in controlled atmospheric (CA) storage of fruits, a practice in commercial use for many years. However, the approach and method application in the gas-exchange process are considerably different from that followed in CA storage. In the gas-exchange process, vacuum is first applied to the food products to remove as much air from within the product as possible. The vacuum is then broken by gas injection, the actual treatment. Depending on the product, the gases used, and the desired result, the process procedure will vary. The gases are chosen to accomplish two primary objectives: 1) kill bacteria on or in the product, and 2) deactivate enzymes. These processes essentially stabilize the product and allow storage without refrigeration. Since the process is normally performed at room temperatures, chemical changes due to temperature extremes are eliminated.

Energy savings of up to 43% have been estimated for gas-exchange processing system (Wheaton et al. 1981). Research on this process has been conducted at the University of Maryland. Because this process is an alternative to current preservation techniques, further research could be conducted to optimize gas types and doses with each product, to determine proper storage container materials, to determine shelf life, and to measure product quality. In addition, consumer acceptance testing will need to be conducted prior to commercialization.

Starch Drying with Solvent Extraction

The drying of starch in water solutions is an energy-intensive operation in the food industry and is specifically for wet corn mill operations. One way of reducing this energy requirement is to mechanically remove some of the water prior to the driers. However, mechanically removing the free water is generally extremely difficult because of the presence of solids, which tend to "hold" the water to their surface and within void spaces between particles. The addition of a second liquid, such as ethanol, may reduce the "attraction" of the free water to the solids by reducing the water's surface tension. When this contacting is completed, the liquid/water removed from the starch could occur in the centrifuge. With the majority of the water removed from the starch, the starch would then be vacuum dried with a minimum of thermal input. Laboratory testing has shown that the above scheme is possible; however, much work is still needed to determine the optimum mechanical separation techniques for the liquid/water and starch solution (Centec Corporation 1981).

Freeze Crystallization

Water removal in such food operations as whey concentration, fruit and vegetable juice concentration, and beet sugar liquor concentration consumes large quantities of energy. Research is needed in heat transfer enhancement of viscous solutions and mechanical research on complete separation of crystallized solvent from the mother liquor at high energy efficiency. Work is also needed in the physics and engineering of hydrate processes for water vapor transfer (Centec Corporation 1981). Because the product is crystallized and removed from a dilute aqueous solution rather than large quantities of water being evaporated, the energy savings can be substantial.

Rapid Sterilization of Canned Foods

Conventional canned foods are sterilized in steam vessels at boiling water temperatures, or up to 250° to 300°F. Sterilization is needed on the surface of the container. As a consequence, the volumetric, thermal-diffusion-driven heating that is currently used wastes both energy and production time. An alternative to the conventional process is the application of specific forms of energy, such as UV, that can perform the sterilization by just treating the

container surface. This process should shorten the processing time and require significantly less energy than current techniques.

Reverse Osmosis

The use of reverse osmosis membranes for water removal could partially replace the need for energy-intensive evaporation systems when concentrating fruit and vegetable juices, sugars, beverages, and starches. A single-pass reverse osmosis unit should require about 30 Btu (fossil-fuel basis) per pound of water removed versus about 300 to 1000 Btu per pound of water for multiple and single effect evaporators. Although some commercialization has been achieved, much work is required to identify the proper membranes and to perfect a system capable of extended operating times (Centec Corporation 1981).

3.7 STONE, CLAY AND GLASS

The stone, clay and glass industries (synonymous with glass, cement and ceramics), SIC 32, consumed over 1.22 quads in 1976. This energy cost the industry some \$2.7 billion or about 8.6 cents per dollar of product shipped.

Generalized process flows for the glass and cement industries are shown in Figures 3.20 and 3.21. Energy usage is dominated by the thermal processing steps (e.g., calcining, melting, drying, sintering, heat treating). Over 80% of the energy consumption was used in thermal processing (furnace heating) in 1976 (Hopp et al. 1981). The remainder was used in forming operations, crushing and grinding, space heating and cooling, material handling, etc. (Oak Ridge Associated Universities 1980).

General analysis shows that a significant potential for energy savings still exists in these processes. For example, the production of Portland cement clinker should theoretically require 430 kcal/kg. In practice, however, the process requires 720 to 1200 kcal/kg, with 800 kcal/kg being a typical value for modern plants. Physical processes such as grinding also leave significant room for improvement. Current grinding processes are less than 10 to 15% efficient.

FIGURE 3.20. Generalized Process Flow Diagram for Glass Production

FIGURE 3.21. Cold Processing in the Generalized Process Flow for Cement Production

Much of the equipment in use is older but is being replaced with state-of-the-art equipment as the old equipment wears out. Generally, it is economic to run thermal processing equipment until it needs rebuilding; then measures to improve or replace with more energy-efficient equipment can be taken. For example, in 1980 the average age of cement kilns in the U.S. was about 23 years, significantly older than in Japan and Europe. The cement industry has had a low return on investment for the last 15 years, averaging 7.5%. Therefore, capital is not freely available for more efficient equipment.

R&D in the cement and concrete industries in the U.S. is very limited, with the investment amounting to less than 0.03% of cement sales or 0.01% of concrete sales. Available funds must compete with more immediate needs such as the purchase of capital equipment to comply with environmental regulations. Consequently, there is almost no basic or scientific research under way that would lead to entirely new processes (O'Hare and Salzano 1981). Current research is evolutionary at most and is not aimed at understanding the process fundamentals. Also the U.S. has no centers for scientific and technical education in cement and concrete technology. These comments regarding the cement industry are generally true for the other glass and ceramics industries.

Glass, cement and ceramics products are inseparable from their basic raw materials and processing. Processing requirements are largely determined by the characteristics of available raw materials (minerals and chemicals), as well as the desired product characteristics. In each of the industries most of the energy is used to thermally process the materials at a temperature and time required to promote desired chemical and physical changes in the materials; only a small amount of energy is used in grinding and forming. The thermal processing is performed in furnaces of various types; therefore, furnace design and heat recovery have been most important to energy conservation. As improvements in these technologies are developed and become economically viable, they will be adopted by this industry.

3.7.1 Alternative Industrial Materials Processes

Innovative processing ideas requiring long-term high-risk R&D in the glass, cement and ceramics industry has received little attention, probably because no basic research is being done and R&D funds are scarce. This industry is heavily biased toward updating existing processes using known technology (e.g., increased insulation, waste heat recovery) or employing economic trade-offs with existing competing processes (e.g., electric furnaces replacing gas furnaces for glass melting).

The products' desirable properties and costs are fundamentally controlled by the raw materials (minerals) used, the processing properties of which vary from site to site. Small improvements in thermal efficiency, and potentially larger cost reductions, may be obtained through materials research in existing processes (e.g., grinding, mixing, feeding furnaces, and furnace temperature cycles), which lead to shortened processing times or lower peak temperatures. For example, a large glass manufacturer studied melting characteristics of sodium borosilicate glass batch components over a 5-year period; the result was a 15% reduction in melting cost and reduced pollution control costs. Of course, predicting whether this type of materials research will result in cost or energy savings large enough to justify the research expenditures is usually difficult.

From a national viewpoint, this type of materials processing research must be done in two stages: 1) improved basic understanding applied to a specific industrial scale process and set of industrial raw materials, and 2) additional R&D to apply the lessons learned in stage 1 to individual industrial plants with their unique raw materials and processing equipment. Presumably, significant first-stage results could be modified for the specific process and raw materials at each processing plant.

Because the little R&D that the industry can afford to conduct would result in evolutionary improvements, the industrial representatives contacted heavily emphasized this category of alternatives. Processes that arose during conversations with the representatives included the following:

- Durability in electric glass melting furnaces is a problem due to molten glass interaction with refractories. Fundamental studies are

needed on electric current flow, heat distribution, effects of batch components and impurities, etc. Existing work is limited to engineering level improvements in existing furnaces.

- Fundamental studies are needed of cement clinker grinding, e.g., waiting one day after the rotary kiln step reduces grinding energy 10% compared to immediate grinding.
- High-temperature filters that separate ash from process gas would allow electrical generation.
- New, chemically different cement systems are needed.
- Grinding research is needed on better mills such as those using waste heat to generate steam to then grind raw materials (e.g., quartz for cement production) in opposed jet mills.
- Optimization of the grinding, mixing, pelletizing, etc., of raw materials is needed to promote faster and more efficient calcining, melting or sintering of cement, glass and ceramic materials.

The high energy intensity of this industry, combined with the prevalent use of very high temperature processes, indicates that revolutionary alternative processes can have a significant impact on energy as well as productivity. One of the advanced processes identified, the cold processing of cement, would eliminate these high temperature requirements. A second process, submerged combustion of glass, would significantly reduce the required residence time in the furnace. An alternative "cold" glassmaking process via some chemical processing is an intriguing idea but has not been posed to date. The third process, involving the preprocessing of ceramic materials, would lower the required processing temperatures. These processes are further described below.

Cold Processing (Chiogiogi 1979)

Cold processing appears to be the most revolutionary alternative process proposed in the cement industry. Cold processing in the generalized process flow for cement production is shown in Figure 3.21. Cold processing would eliminate the need for high temperatures in the conversion of the material. This method was originally proposed by C. J. Schifferle and J. J. Coney. They proposed that quicklime and an argillaceous component, such as shale or

clay, be chemically combined by grinding the components together in a conventional ball mill. The only thermal process that remains is the calcining of limestone by conventional means. Thus, a significant energy conservation potential is anticipated.

Cold processing has reportedly been demonstrated in a pilot plant and has produced hydraulic cement with characteristics and properties that are similar to those of Portland cement. However, the status of this effort is unknown.

Due to the radically new direction offered by cold processing and the potential for energy savings, this appears to be an area that should be explored further.

Submerged Combustion (Chioggiogi 1979)

In submerged combustion, glass is rapidly heated in a glass furnace. In one arrangement, burners are placed at the bottom of the furnace, causing much greater heat transfer through the vigorous stirring of the glass melt. Because of the rapid processing that results from submerged combustion, furnace energy consumption could be reduced by an estimated 50%.

A major technical barrier in this process has been the formation of a large number of bubbles in the glass. This currently requires extensive additional refining. A possible technique to avoid this problem might be the use of chemicals to prevent bubbles from forming and to accelerate the processing.

Preprocessing Techniques for Ceramic Materials (O'Hare and Salzano 1981)

Broadly defined, preprocessing techniques for ceramic materials would involve the prereaction of ceramic materials that will reduce the required firing temperature. In addition to saving energy, this process is anticipated to increase the quality of the product and reduce the cost.

The primary objective of research in this area is expected to be in understanding fine-particle processes. This would involve fundamental chemistry and materials property study in examining the value of preconditioning with various ceramic formulations.

3.8 TEXTILES

The textiles industry converts natural and synthetic fibers into fabrics. Other associated industries produce fibers or convert fabrics into clothing, upholstery, rope, etc. Textile products span the range from lace to carpet, thread to rope, and include yard goods. In 1976, the industry used 2.6% of all industrial energy, or about 0.33 quads (Hopp et al. 1981). This energy cost slightly less than \$1 billion, which is 2.7% of the value of textile shipments, or 4.5% of materials costs (Oak Ridge Associated Universities 1980).

Textile manufacturing processes vary considerably depending upon the fiber form and the desired products. Fibers (e.g., cotton, linen, wool, silk, nylon, rayon) are first spun into yarns and then woven or knitted into fabric. The fabric is finished either to remove impurities from the cloth (e.g., desizing, scouring, bleaching, mercerizing, bulking, and carbonizing) or to add chemicals to the cloth (e.g., dyeing, printing, resin treatment, waterproofing, flame-proofing and soil repellence).

Although the production of textiles is now highly automated and mechanized, many of the basic processes have not changed in the industry's five to six thousand year history. Processes such as fiber and yarn manipulation are the same as those conducted by the Swiss lake dwellers in neolithic times.

Textile processes are of two basic types, either dry (spinning, knitting, weaving, etc.) or wet (dyeing, sizing, washing, drying, etc.). The dry processes use electrically driven mechanical devices and appear to have limited energy conservation potential. On the other hand, wet processes, which account for about 60% of the textile industry energy use, offer good conservation potentials (Cook et al. 1977). Wet processes primarily use fossil fuels to heat hot baths, to produce steam, or to dry fabric. Fossil fuels and steam account for 86% of the energy used in knit fabrics and 91% of the energy used in woven fabrics (Oak Ridge Associated Universities 1980). Accordingly, conservation efforts in the industry have been and are being directed toward improved heat transfer techniques, reclamation and use of waste heat, processes and equipment that require less water, and the use of waste products as fuels.

Although the textile industry itself is very old, its machinery is relatively new. In 1975, some 70% of the equipment was less than 15 years old. The remaining 30% was mainly weaving and dry process equipment. Therefore, the wet processing equipment is relatively new. Even with such relatively new equipment, substantial savings could be achieved via retrofits or equipment replacements, many of which are economically feasible (Oak Ridge Associated Universities 1980).

R&D within the industry has been addressed largely to process and product improvement and response to environmental regulations. These activities account for more than 85% of the R&D expenditure. Less than 10% goes to product or process innovation and less than 5% of the research budget is directed at basic research (O'Hare and Salzano 1981). Much of the research performed for the industry is being conducted by textile industry suppliers of fibers, chemicals, etc. Considerable research is also conducted with private funding at places such as the Textile Research Institute, Princeton, New Jersey, and the Institute of Textile Technology, Charlottesville, Virginia. R&D has been conducted at the university level (Georgia Tech and North Carolina State) and at the Southern Regional Research Center, USDA. Outside of the U.S., textiles research is concentrated in Europe and Japan.

Because of its disperse nature, the textile industry suffers from low capital generation. Therefore, although the industry may be ripe for innovation, the pursuit of such innovation remains at a low level. O'Hare and Salzano (1981) note a massive library of patents, research results, and general information appears to be available but is not being used.

3.8.1 Alternative Industrial Materials Processes

Although the basic, energy consumptive processes used in the industry are extremely old, there appear to be only a few proposals for innovative processes requiring long-term R&D. The lack of revolutionary ideas is due to the following reasons: 1) process and procedural modifications at the engineering level are yielding significant energy reductions; 2) privately funded research is being done to reduce the quantity of water (and the thermal energy) used in wet process; and 3) when innovative ideas arise within the industry they are

likely to remain company proprietary for competitive reasons, at least until the ideas are developed and implemented.

Process and procedural modifications that are resulting in significant energy savings are reviewed by Cook et al. (1978), O'Hare and Salzano (1981), and Oak Ridge Associated Universities (1980). These modifications include waste heat recovery, dye bath reuse, foam processes (in place of bath processes), mach nozzle drying, exhaust gas reclamation, altered synthetic fibers requiring less energy in wet processing, radiation bleaching, curing and fixation processes, and improved moisture measurement in fabric drying.

A. D. Little, Inc. has examined knit fabric mills and woven fabric mills and has identified a large energy saving potential through advanced technology retrofit (Oak Ridge Associated Universities 1980). In knit fabric mills, A. D. Little has estimated that energy use can be reduced by 50%. The advanced technology measures that were included are 1) an air/vacuum extractor as an alternative to the conventional hot air dryer, 2) equipment to reduce water volume throughput, 3) recycled cooling water from dyeing, 4) the elimination of steam, and 5) the reduction of natural gas.

In woven fabric mills, a 57% reduction in energy use was identified through advanced technologies. These advanced steps include 1) recycling polyvinylalcohol (PVA) back to desizing, 2) recycling hot water back to desizing, 3) using high-efficiency equipment to reduce water volume, 4) using an extra recycle loop for washing, and 5) using heat recovery for heat set operations during preparation, after polyester drying, and for final heat set.

According to industry contacts, R&D projects are currently under way in the areas of low energy dyeing (at the Textiles Research Institute), foam processing (at most major textile companies), and low energy sizing.

Although the area of revolutionary alternative processes has been largely unexplored, a few candidate processes have been identified. The revolutionary processes requiring long-term research that have been identified include the formation of garments by spray fabrication, the direct application of process chemicals to fibers and fabrics, and the production of generic fibers from renewable resources.

Formation of Garments by Spray Fabrication

This process involves the direct formation of garments through the spraying of fibrous material (O'Hare and Salzano 1981). Spray formation could substitute for several conventional processing steps as shown in Figure 3.22. Because this option still appears to be largely conceptual, the details of the process are not available. Issues such as fiber-to-fiber bonding will be important. The process is a candidate to substitute for the initial mechanical spinning and weaving of the fabric. If combined with the direct application of process chemicals to fibers or fabrics, the process may even substitute for other intermediate steps in the formation of a garment, including singeing, sizing, mercerizing, and bleaching operations. Spray formation would thus eliminate many of the current intermediate steps and significantly reduce drying and heating requirements.

Direct Application of Process Chemicals to Fibers and Fabrics

The primary objective of this process is to apply process chemicals to textile products with the minimal use of liquids (Washington Scientific Marketing 1978). This would eliminate intermediate washing and drying steps and would reduce the energy required for final drying. Techniques that have been proposed include the following:

- electrostatic deposition of dyes
- gaseous reactants in preparation
- vapor phase reactants
- spray application of reactants.

A major challenge to the process will be in treating fiber and fabrics uniformly or in a controlled pattern.

Generic Fibers from Renewable Resources

This process would involve developing new families of fibers that are derived from renewable resources (O'Hare and Salzano 1981). As in the case of spray formation, this process is still conceptual and without much detail. The specific techniques by which useful fiber can be derived from biomass need to be explored further and the range of possible materials needs to be identified.

FIGURE 3.22. Conventional Textile Processing Sequence and the Alternative Spray Forming Process

This process is directed at feedstock substitution more than at energy conservation. The process is included here because it potentially could eliminate petroleum as a source of synthetic fibers.

3.9 GENERIC REVOLUTIONARY PROCESSES

The other category of revolutionary processes that was not directly addressed in this study includes those that stem from generic technologies. That is, certain innovative approaches readily lend themselves to applications across a variety of end uses or standardized industrial processes or process steps. Conversations with many researchers in the energy conservation field revealed that these are the types of ideas that are most commonly associated with the idea of revolutionary processes. Because of the frequency with which these types of processes were posed by other researchers, they will be discussed, though briefly, for completeness.

The possibilities for generic revolutionary technologies and processes span a wide breadth of ideas. However, many technologies share certain common characteristics that are useful in describing why these technologies or processes are considered revolutionary. Two important characteristics are the general concept being exploited and the general concept or conceptual process being replaced. The general concepts and general processes replaced for the generic processes posed here are illustrated in Table 3.13. Also shown are examples of the types of generic revolutionary ideas offered.

The general concept behind the processes illustrates the revolutionary principle involved. By identifying these principles the innovator can direct his efforts toward various specific means of exploiting the concept. That is, these concepts may point toward other uses to which the innovative idea might be applied. The generic processes collected in this study were categorized into eight general concepts: physical/electrical separations, materials processing via alternative thermodynamic states, highly specific induction of reactions, surface processes, highly reduced use of solvents, concentrated energy processing, unique materials properties, and biotechnology. Technologies that were most frequently mentioned were the physical/electrical separations, the application of highly specific forms of energy to induce

TABLE 3.13. Example Generic Materials Processing Alternatives

Concept	To Eliminate	Examples
Physical/Electrical Separations	Thermal separations	Membrane separation Electrolytic processes
Materials Processing via Alternate Thermodynamic States	Multiple step processing via traditional thermodynamic state changes	Critical fluid extraction Plasma materials processing
Highly Specific Induction of Reactions	Diffusional loss of energy	Laser chemistry Electrochemical processes Photochemical processes Catalysts Induced fields (electrostatic, magnetic, ultrasonic, UV)
Surface Processes	Thermal diffusion times bulk heating	Infrared, microwave, and radio-frequency drying UV curing – use of photoinitiators Electron and laser technologies for curing
Highly Reduced Use of Solvents	Drying requirements Consumption of solvents	Electrostatic charge to attract coatings Solventless systems Foams
Concentrated Energy Processing	Diffusional and other effects of slow processing	Homopolar pulsed heating
Unique Materials Properties	Unnecessary use of homogeneous materials Penalties of conventional materials use	Laminates – resins between layers of aluminum or steel Amorphous metals
Biotechnology	Thermally intensive chemical processing	Biocatalysts Biological separations

reactions, and surface processes. All three concepts clearly share the characteristic of minimizing the use of thermal energy, which is the common driving force in conventional processes.

The second column of Table 3.13 illustrates the general types of processes that are being replaced. These processes being eliminated are related to the concept of "irreducibles" posed by Charles Berg and described in the introduction. Berg (1980) noted that an irreducible is associated with each site of entropy production. Rather than attempt to illustrate each process at this level, the table shows the general process that is replaced by the revolutionary technique. Approaching the processes at this level is useful because noting the types of processes eliminated helps identify a broad range of areas where the revolutionary technology may apply. This column clearly shows that the general use of thermal processing of materials has a wide choice of alternatives. Among the candidates for replacement are thermal separations processes, the diffusional loss of energy in thermally driven chemical reactions, thermal diffusion due to bulk heating, drying requirements, and material limitations of conventional products.

The last column of Table 3.13 contains examples of the revolutionary generic ideas that were posed by other researchers. Again, note that this list is not comprehensive but only a preliminary list of examples. It is, nonetheless, useful to include the list because it does offer several intriguing ideas that are still in their infancy in their development. The most frequently mentioned technologies include laser chemistry, microwave and radiofrequency heating, photochemical and electrochemical processes, new forms of membrane separation, and biocatalysis.

Another intriguing area that is not well understood is the area of induced fields. These fields include those generated by electrostatic, magnetic, ultrasonic, and UV sources. Induced fields are controlled fields that are directed toward facilitating a certain process such as a chemical reaction, the physical reduction of solid materials, the movement fluids, or a biological process. They have been shown to have beneficial effects in reducing diesel engine emissions, increasing rates of biological growth, and reducing the formation of scale. The fields also may be useful in comminution

processes, such as material size reduction and raw materials beneficiation. The efficiency of current processes is less than 10% and the overall energy consumed is significant. For example, 60% of the electricity used in cement making goes to clinker grinding (INMAB 1981).

Although the potential uses for induced fields appear quite broad, explanations regarding the mechanisms involved in these processes have yet to be proven.

The list of example processes also contains revolutionary technologies that were discussed in the previous sections on industry-specific advanced materials processes. These processes include membranes that were mentioned for use in petroleum refining and chemical processing, laser chemistry in chemical processing, and the use of plasmas in the processing of materials such as steel and aluminum. These technologies have been repeated here because their generic nature may make them applicable to yet-discovered materials processing requirements. It also illustrates that in some cases, revolutionary ideas applied to specific processes can be extended to other processes.

4.0 SUMMARY AND CONCLUSIONS

This study provided a preliminary identification of revolutionary industrial materials processes that have the potential for significant energy savings and that require long-term research. The materials processing industries investigated here include chemicals; iron and steel; aluminum; petroleum refining; paper and allied products; food and kindred products; stone, clay, and glass; and textiles.

The primary focus of this study was on identifying candidate revolutionary materials processes that require long-term research. In this identification, the study was not restricted to those processes that have been lab tested, although several have been extensively proven. Rather, a breadth of candidates was explored, some of which are still in the conceptual phase. The stage of development of each process therefore varies greatly. Certain ideas, such as direct steelmaking, are candidates for applied and developmental research, whereas other processes, such as the dry forming of textiles, still require more basic research.

Additionally, this study was directed toward a review of those ideas for revolutionary processes that have already been suggested other researchers and innovators. The study was therefore a scoping effort to review the extent to which revolutionary processes are being discussed in each of the industries and to indicate if a thorough study is warranted.

In total, 45 candidate processes were identified in this investigation. These processes are summarized in Table 4.1. The chemical and the iron and steel industries presented the most well-developed candidates, whereas those processes identified in the pulp and paper and textiles industries were the most speculative. The distribution of candidate processes among the various industries was as follows:

- chemical - 7
- iron and steel - 6
- aluminum - 4
- pulp and paper - 9
- petroleum refining - 5

TABLE 4.1. Summary Table of Advanced Industrial Materials Processes

Process	Process(es) Displaced	Potential Energy Savings (relative to current process)	Technical Barrier(s)	Current Research
<u>Chemicals Industry</u>				
Bio-technology	Extreme process conditions Multiple step processes	Mod/High	Purification and separation Maintaining microbes under large flow rate processing Raw materials	Mod
Photo-chemistry	Thermal activation of reactions	Mod	Photo-chemical reactors	Low/Mod
Catalysts	Extraneous reactions Thermal activation of reaction	High	Mechanisms of catalysis Recycling of rare constituents Adopting process design and control	High
Advanced Reactor Design	Conventional Chemical Reactors	Mod	Understanding reaction mechanisms	Low/Mod
Membrane Separation	Thermal separation	Mod		Mod
Super Critical Fluid Extraction	Conventional distillation	50%	Lack of fundamental engineering data	Mod
Freeze-Crystallization	Conventional distillation	75-90%	Process applications Combination with other separation methods	Low

TABLE 4.1. (contd)

Process	Process(es) Displaced	Potential Energy Savings (relative to current process)	Iron and Steel Industry		Current Research
				Technical Barrier(s)	
Direct Steelmaking	Conventional processes (coke oven-blast furnace-BOF)	20-30%		Containment of reactions - durability of refractory linings	Low
				- presence of oxidizing and reducing reactions	
Ore-to-Powder Systems	Conventional processes (coke oven-blast furnace-BOF)	40%		Magnetic separation Chemical leaching of the ore	Low
Plasma Steelmaking	Conventional processes (coke oven-blast furnace-BOF)	Low		Plasma gun High electricity requirement	Low
Plasma Smelting	Blast furnace	Low/Mod		High electricity requirement Plasmas and plasma guns	Low/Mod
Direct Casting	Deformation processing steps	20%		Design for high quality high production - nozzle blockage	Low
Electroforming	Conventional processes (coke oven-blast furnace-BOF)	Low		Slow process Requirement of many modular units	Low

TABLE 4.1. (contd)

Process	Process(es) Displaced	Potential Energy Savings (relative to current process)	Technical Barrier(s)	Current Research
<u>Aluminum Industry</u>				
Carbothermic Reduction of Ore	Bayer alumina process Hall-Héroult smelting	Fuel switch from elec- tricity to coal	Furnace refractory	Mod
Carbothermic Reduction of Alumina	Hall-Héroult smelting	Fuel switch from elec- tricity to coal	Formation of aluminum com- pounds with carbon, oxygen, and nitrogen	Low/Mod
Aluminum Trichloride Electrolysis	Hall-Héroult smelting	40%	Handling corrosive Al-Cl ₂ Maintaining purity Maintaining an air-free and water-free environment	High
Aluminum Sulfide Electrolysis	Bayer alumina process, Hall-Héroult smelting	50%	Production of Al ₂ S ₃ Sulfur recovery High carbon requirements	Low/Mod

TABLE 4.1. (contd)

Process	Process(es) Displaced	Potential Energy Savings (relative to current process)	Technical Barrier(s)	Current Research
<u>Petroleum Refining Industry</u>				
Membrane Separation	Distillation stripping Absorption (thermal separation)	Mod/High	Separation of organic fluids	Low
Catalysis	Reduced reaction temperatures	Mod/High	Fundamental understanding of catalysts	Mod
Genetic Engineering	Chemical process (e.g., cracking)	Mod/High	Reactor design Maintaining microbes under large flow rate processing	Low
Extractive Distillation	Reduced distilla- tion temperatures	Low/Mod	Identification of solvents	Low
Replacing Combustion Processes	Combustion	Low/Mod	Alternative chemical reac- tions to use of fuel	Low

TABLE 4.1. (contd)

Process	Process(es) Displaced	Potential Energy Savings (relative to current process)	Technical Barrier(s)	Current Research
<u>Pulp and Paper Industry</u>				
Dry Forming	Kraft pulping Conventional papermaking	25-50%	Dry bonding mechanisms	None
Pulping Through Solvent Extraction of Lignin	Kraft pulping	--	Developmental appropriate solvents	None
Lignin Biodegradation	Mechanical reduction Digester	Mod	Reactor design	None
Autocaustization of Pulping Chemicals	Lime kiln	40-50%	--	None
Low Energy Chemistry in Pulping	High thermal processing requirements	Low	Application of laser-induced reactions	None
Carbothermic Reduction of Sodium Carbonate	Lime kiln Lime slacking	Mod/High	--	None
Alternative Debarking	Conventional debarking	Mod	Application of sonic, micro- wave, or other techniques	None
By-Product Recovery	Combustion of lignin and groundwood	--	Degrading processes Product synthesis	Low/Mod

TABLE 4.1. (contd)

Process	Process(es) Displaced	Potential Energy Savings (relative to current process)	Food and Kindred Products Industry	Technical Barrier(s)	Current Research
Modified High Fructose Corn Syrup Process	Wet milling 1/2 drying requirement	30%	--		Low
Genetic Engineering	Drying preservation	High		Basic research on genetic engineering techniques (e.g., enzyme production)	High
Alternative Food Preservation Methods	Refrigeration Thermal sterilization	Mod		Dosages Time effect Application techniques Adverse effects Altering food properties	Low/Mod
Preservation by Gas Exchange	Refrigeration	40%		Optimal gas types and doses Storage containment	Low
Starch Drying with Solvent Extraction	Thermal drying	Low/Mod		Optimal second liquid Mechanical separation techniques	Low
Freeze-Crystallization	Thermal drying	Mod/High		Separation Heat transfer enhancement of viscous fluids Hydrate process	Low

TABLE 4.1. (contd)

Process	Process(es) Displaced	Potential Energy Savings (relative to current process)	Technical Barrier(s)	Current Research
<u>Food and Kindred Products Industry (contd)</u>				
Rapid Sterilization of Canned Foods	Steam Sterilization	Mod	Application of UV	Low
Reverse Osmosis	Thermal separations	90-99%	Membrane development	Mod/High
<u>Stone, Clay, and Glass Industry</u>				
Cold Processing	Cement kiln	70-80%	--	Low
Submerged Combustion	Conventional glass furnace	50%	Formation of bubbles in glass	Low
Preprocessing of Ceramic Materials	High temperature firing	Mod	Fire-particle processes	None

TABLE 4.1. (contd)

<u>Process</u>	<u>Process(es) Displaced</u>	<u>Potential Energy Savings (relative to current process)</u>	<u>Technical Barrier(s)</u>	<u>Current Research</u>
<u>Textiles Industry</u>				
Spray Fabrication of Garments	Spinning Weaving Intermediate wash- ing, drying and bleaching	Mod	Fiber bonding	None
Direct Application of Process Chemicals	Intermediate wash- ing and drying	Mod	Uniform treatment of fabrics	Low/Mod
Generic Fibers from Renewable Resources	Substitution for petroleum-based synthetics	--	Techniques of deriving fiber from biomass	None

- food processing – 8
- stone, clay, and glass – 3
- textiles – 3.

In the table, the distribution of processes among the industries should not be interpreted to indicate the potential that exists for revolutionary changes. Rather, if these numbers are a measure of some characteristic, they may indicate the degree of thought that has been directed toward revolutionary alternatives.

To help define the processes, other types of information were also sought in addition to descriptions of each candidate process. This information is also presented in Table 4.1 and includes the process or processes displaced, estimates of the energy conservation potential, samples of the major technical barriers that need to be overcome, and the level of current research. Because some of the processes are still conceptual, not all of the information was available for all of the processes. However, the table reflects currently available information.

The first column of Table 4.1 lists the processes identified in each of the industries. Three categories of processes recur in this list. The first category is the use of chemical and biological systems. These systems are used in ore-to-powder steelmaking, cold processing of cement, and biodegradation of lignin in pulp processing. The second category is the application of specific forms of energy such as ultraviolet radiation in sterilization, microwave and radiofrequency drying, and lasers and induced fields in driving chemical reactions. The third common category of revolutionary ideas includes those processes that combine several energy-intensive steps in existing processing into one step. Examples include direct steelmaking, direct casting, the carbothermic production of aluminum, and the dry forming of paper.

The second column of the table summarizes the existing process or processes that would be replaced by the revolutionary technique. The information presented in the table clearly illustrates one overriding theme: the elimination or reduction of thermally driven processes. These thermally driven processes include thermal separations, thermal activation of reactions, bulk thermal heating, and multiple thermal materials processing steps, such as the

elimination of separate coking, ironmaking, and steelmaking furnaces in the production of steel. The primary targets of the alternative processes are these thermally intensive processing steps, many of which date back centuries and even millennia. Future developments in materials processes may therefore see the phasing out of such energy-intensive technologies as the cement kiln, the coke oven, the blast furnace, the steelmaking furnace, the Kraft pulping process, and the widespread use of distillation columns.

The third column of the summary table contains estimates of the energy savings potential of several of the revolutionary processes compared to the conventional processes being displaced. Because many processes have not been thoroughly analyzed, specific calculations of energy savings were often not available and therefore were not provided. Based upon the available information, the following ratings of "high," "moderate," or "low" were given:

- An estimate of "high" indicates a possible savings of 50% or more over the conventional process.
- A "moderate" rating indicates that the improvement will likely range between 20 to 50%.
- A "low" rating would be for improvements of 20% or less.

Although these estimates are broad, they illustrate the extent of knowledge in this area.

When the energy savings potential of the various processes are viewed, it is important to remember that this is only one aspect of the overall productivity improvement that might be anticipated. Production speed, labor requirements, capital requirements materials requirements, and product quality are other process characteristics that are each extremely important in the overall evaluation of the process' worth. For example, in addition to reducing energy requirements by 20 to 30%, direct steelmaking may also reduce capital costs 30 to 35%, reduce labor costs 10 to 15%, and is likely to be flexible enough to operate at a wide range of production levels.

The fourth column of the summary table lists some of the technical barriers associated with the revolutionary processes. Because the identification of technical barriers was only a secondary objective in this study, these bar-

riers are only presented as examples of the problems to be overcome. Again, in many cases the processes were not developed well enough to permit precise definition of these barriers. However, the table does show that certain basic issues did recur in the list. These issues include a better fundamental understanding of the mechanisms of catalysis and mitigating corrosion problems in high-temperature processing conditions.

The final column of the table indicates the extent of current domestic research in the various processes. The four levels of current research can be interpreted as follows:

- A "high" rating indicates that a significant amount of research is under way, at least some of which relates to the revolutionary elements of the process.
- A "moderate" rating indicates that some research is under way but most is likely to be related to near-term issues.
- A "low" rating indicates very little research is under way.
- "None" indicates that no research is being conducted.

The chemical industry was found to be the only industry with an active long-term research program under way to address these processes. The chemical industry seems to be at least moderately involved in each of the general areas studied here. The aluminum industry appears to follow the chemical industry in ongoing research. As with the chemical industry, the aluminum researchers appear to be investing in long-term ideas. Information indicates that the remaining industries are carrying out little or no research into the revolutionary processes discussed here. The steel industry is a particularly striking example. This is an industry in critical need of modernizing, in which many ideas for revolutionary processes have been advanced, yet significant research or development appears to be under way.

An alternative way of viewing the revolutionary processes is through the general concepts or principles that generically describe the replacement of one process with another. By viewing these concepts generically, they may then be extended to other processes to stimulate the conception of more innovative alternatives. Table 4.2 summarizes several of the most common

TABLE 4.2. Generic Categories of the Revolutionary Processes

Current Process	Alternative Process	Example Revolutionary Processes
High Temperature Materials Conversion	Chemically controlled conversion Biologically controlled conversion	Ore-to-powder steelmaking Cold processing of cement
Thermal Separation	Physical separation Biological separation Magnetic separation	Membrane separations in chemicals, petroleum refining, and food processing Biological separations in chemical processing, petroleum refining, and food processing Magnetic separations in ore-to-powder steelmaking
Drying/Wet Processing	Dry materials processing	Dry forming of paper Modified high fructose corn syrup process Spray dyeing of garments
Physical Reduction	Biologic degradation Chemical degradation Ultrasonic processes	Biological degradation of lignin in pulping Pulping through solvent-extraction of lignin Ore-to-powder steelmaking Cold process of cement Ultrasonic debarking
Bulk Heating	Radiative surface heating Laser chemistry	Sterilization of food containers Laser activated chemical processing Lasers in low energy pulping
Refrigeration	Sterilization Genetic engineering	Sterilization for food preservation Genetic engineering of crops
Multiple Processing Steps	Single step processes Multiple steps in a single reactor	Biological reforming of petroleum products Ore-to-powder steelmaking Direct steelmaking Direct coating Carbothermic production of aluminum from ore Dry paper forming Modified high fructose corn syrup process Cold processing of cement Spray forming of garments

categories of those general concepts. These categories are high-temperature materials conversion, thermal separation, drying/wet processing, physical reduction, bulk heating, refrigeration, and the use of multiple processing steps. Also shown are the types of processes that are used to replace the conventional process and some specific examples from the processes identified in this report.

Perhaps the most ubiquitous and energy-consuming process is the high-temperature conversion of materials, such as the iron blast furnace, the steelmaking furnace, the cement kiln, and the glass furnace. Energy used in industrial furnaces has been estimated to account for 10% of all the energy used in the industry (Imhoff 1982). Alternatives to high-temperature thermal materials processing include the chemically and biologically controlled conversion of materials. Examples of these alternatives that were discussed in this report include ore-to-powder steelmaking systems and the cold processing of cement. Thermal separations processes are also a very large user of energy. Distillation processes consumed an estimated 2 quads of energy in 1980 (DOE 1980). Some of the alternative processes that have been designed and that circumvent the high energy demands of distillation include physical separation, biological separation, and magnetic separation. Examples of such alternative processes include membrane separations in chemical processing, petroleum refining, and food processing; biological separations in chemical processing, petroleum refining, and food processing; and magnetic separations in ore-to-powder systems.

A third category of industrial process that is also very energy-intensive is drying. Drying processes consumed an estimated 1.4 quads of energy in 1977 (Reay 1978). Revolutionary ways of minimizing this requirement are through dry materials processing routes. Examples of this include the dry forming of paper, the modified high fructose corn syrup process, and the spray fabrication of garments.

The physical reduction of solid materials is another very energy-inefficient route in common practice. The physical reduction of materials in mining, for example, is asserted to be less than 10% efficient in its use of energy (NMAB 1981). Alternative methods of achieving the same service include

biological degradation, chemical degradation, and reduction via ultrasonic processes. Examples of these processes include the biological degradation of lignin in pulping, pulping through the solvent extraction of lignin, the processing of ore in ore-to-powder steelmaking systems, the cold processing of cement, and the use of ultrasound to facilitate the debarking and reduction of wood stock.

The heating of entire volumes of material when only surface treatment is necessary is a fifth category of processes. For example, in conventional container sterilization and coat-curing processes, the entire volume of the can is heated to achieve the desired service. Berg (1980) and Schmidt^(a) have both pointed out that this volumetric heating is an efficient use of energy and that the volumetric thermal diffusion rates slow production. The solution in the case of coat curing was the application of UV radiation to a photosensitive coating. The UV activates photoinitiators in the coating that in turn cause polymerization and hardening. The general category for this type of alternative process might therefore be termed radiative surface heating. Another potential application of this concept is in the sterilization of containers in the food industry.

Applying specific forms of energy to activate chemical reactions is another concept related to the application of specific forms of energy to overcome the problem of volumetric thermal diffusion. One example of this concept is the use of lasers in chemical processing.

A sixth area of conventional processes that may benefit from the development of revolutionary ideas is refrigeration. The substitution for this process is particularly relevant in the food-processing industry where techniques such as sterilizing to preserve food and genetic engineering have been posed as alternatives. Sterile milk and the genetic engineering of crops requiring minimal preservation are examples that are discussed in this report.

Finally, a seventh area in which conventional processes may be replaced is in the use of multiple materials processing steps. Examples of materials

(a) Personal Communication with P. S. Schmidt from the Electric Power Research Institute (1982).

processing sequences are present in virtually every industry and every major industrial materials product. The conceptual alternative, of course, is the development of single-step processes or multiple steps in a single reactor. Examples of this change in processing are numerous and include the biological reforming of certain petroleum products from crude oil, the ore-to-powder processing of steel, direct steelmaking, direct casting, the carbothermic production of aluminum from ore, dry paper forming, the modified high fructose corn syrup process, cold processing of cement, and the spray forming of textile garments. This concept of multiple to single processing steps provides the least technical guidance of the conceptual changes discussed here. However, this category does show the dramatic potential available from radical changes in major materials processes.

Because the industries and processes covered in this report are diverse, precise conclusions are difficult to make. The industries can be broadly categorized as those that are composed of many different subindustries and many different processes, and those that are dominated by a primary processing sequence. The chemical and food processing industries are classified by the former category, whereas the iron and steel, aluminum, pulp and paper, petroleum refining, cement, glass, and textile industries are more characterized by the latter category. This diverse nature of the many materials processing industries results in some industries being more well suited to a study into revolutionary processes than others. Other industries are better suited to generic improvements because of their dispersed nature. For example, in food processing, wet cornmilling is the most energy-consumptive industry and evaporation is the most energy-consumptive process. Yet wet corn milling uses only 10% of the industry's energy and evaporation accounts for only 20% of the energy used in wet corn milling, or 2% of the industry's energy. By contrast, the blast furnace processing iron and steel uses 40% of that industry's energy. Similarly, the chemicals industry is composed of a wide variety of subindustries, each with different and specific materials conversion requirements but similar generic processing needs. A generic approach is clearly better suited to this industry.

The extent to which industry is pursuing revolutionary processes varies from moderate in the chemicals and perhaps aluminum industry to low to

negligible in the other industries studied. The abundance of ideas for major innovations follows a similar pattern with the exception of the steel industry, in which several highly promising ideas exist, yet little effort is under way in the U.S. to pursue these ideas. Direct steelmaking and direct casting are highly promising alternatives and they appear to warrant substantive R&D support. It is also worth noting that our major foreign competitors, notably Germany and Japan, are taking a strong interest in technologies such as direct steelmaking and direct casting.

The preliminary list of processes in this report illustrates both the potential and the state-of-knowledge regarding revolutionary industrial materials processes. As a result of industry's primary concern with immediate and near-term production needs, the focus of technological progress has been almost exclusively evolutionary. In most industries, the idea of dramatic productivity improvement through revolutionary materials processes requiring long-term research has been given minimal attention, if any at all. Although information regarding many of the revolutionary processes is still sketchy, much of the information does indicate that major efficiency increases are possible. For example, direct steelmaking and ore-to-powder systems potentially require 30 and 40% less energy, respectively, than conventional steelmaking systems. Membrane separations and freeze crystallization offer up to 90% reductions in energy use when compared with distillation. The cold processing of cement offers a 50% reduction in energy requirements and the dry forming of paper offers a 25% reduction in the energy needed for papermaking.

To assure that the U.S. exploits its most promising conservation options, more thorough innovative thinking is needed in all industries.

REFERENCES AND BIBLIOGRAPHY - GENERAL

- Belzer, D. 1982. Energy Conservation Indicators. PNL-4285, Pacific Northwest Laboratory, Richland, Washington.
- Berg, C. A. 1979. Energy Conservation in Industry: The Present Approach, The Future Opportunities. Council on Environmental Quality, Washington, D.C.
- Berg, C. A. 1981. "Process Integration and the Second Law of Thermodynamics: Future Possibilities." Energy. 5(8-9):733-742.
- Berg, C. A. 1981. "A Suggestion Regarding the Nature of Innovation." Prepared for the Workshop on Energy, Productivity, and Economic Growth, January 12-14, 1981, Electric Power and Research Institute, Palo Alto, California.
- Business Week. July 5, 1982. "A Research Spending Surge Defies Recession." pp. 54-74.
- Chiogioigi, M. H. 1979. Industrial Energy Conservation. Marcel Dekker, Inc., New York, New York.
- Committee on Nuclear and Alternative Energy Systems (CONAES). 1979. Energy in Transition, 1985-2111. W. H. Freeman, San Francisco, California.
- Data Resources, Inc. 1978. Energy Conservation in the Petro-Chemical Industry. Data Resources, Inc., Lexington, Massachusetts.
- Derouette, J. J. 1979. "Application of the Second Law of Thermodynamics to Basic Industrial Processes." Proceedings of the International Seminar Held in Brussels, October 23-25, 1979, D. Reidel Publishing Company, Boston, Massachusetts.
- Gibbons, J. H. 1976. "Long-Term Research Opportunities." In Energy Conservation and Public Policy. Prentice-Hall, Inc., Englewood Cliffs, New Jersey.
- Gibbons, J. H. and W. U. Chandler. 1981. Energy, The Conservation Revolution. Plenum Press, New York, New York.
- Gibbons, J. H. and W. U. Chandler. 1981. Energy: The Conservation Revolution. Plenum Press, New York, New York.
- Gyftopoulos, P. 1974. Study of Effectiveness of Industrial Fuel Utilization. Thermo Electron Corporation, Waltham, Massachusetts.
- Hagler, Bailly and Company. 1981. Government-Sponsored Industrial Energy Conservation Research, Development, and Demonstration. Hagler, Bailly and Company, Washington, D.C.

- Hopp, W. J. et al. 1981. An Overview of Energy Conservation Research Opportunities. PNL-3944, Pacific Northwest Laboratory, Richland, Washington.
- Hopp W. J. et al. 1982. Identification of Energy Conservation Research Opportunities: A Review and Synthesis of the Literature. PNL-3966, Pacific Northwest Laboratory, Richland, Washington.
- Imhoff, C. H. et al. 1982. U.S. Energy Conversion and Use Characteristics. PNL-4175, Pacific Northwest Laboratory, Richland, Washington.
- National Materials Advisory Board (NMAB). 1981. Comminution and Energy Consumption. PB81-225718, National Academy of Sciences, Washington, D.C.
- National Materials Advisory Board (NMAB). 1982. An Assessment of the Industrial Energy Conservation Program, Volume 1: Summary. NMAB 395-1, National Materials Advisory Board, Washington, D.C.
- Oak Ridge Associated Universities. 1981. Industrial Energy Data Book. ORAU-161, Oak Ridge Associated Universities, Oak Ridge, Tennessee.
- O'Hare, T. E. and F. J. Salzano. 1981. Future Raw Materials and Energy Use in Industry - A Research Agenda. BNL-51382, Brookhaven National Laboratory, Upton, New York.
- Reay, D. 1978. "Don't Waste Your Energy Drying Those Solids." Process Engineering. pp. 71-75.
- Reid, R. O. and M. H. Chiogioigi. 1976. "Technological Options for Improving Energy Efficiency in Industry and Agriculture." In Energy Conservation and Public Policy. Prentice-Hall, Inc., Englewood Cliffs, New Jersey.
- Ross, M. H. and R. H. Williams. 1981. Our Energy: Regaining Control. McGraw-Hill, New York, New York.
- Sawhill, J. C. 1979. Energy, Conservation and Public Policy. Prentice-Hall, Inc., Englewood Cliffs, New Jersey.
- Schmidt, P. S. 1981. Industrial Electrification: A Framework for Development. Electric Power and Research Institute, Palo Alto, California.
- Solar Energy Research Institute (SERI). 1981. A New Prosperity, Building a Sustainable Energy Future. Brick House Publishing, Andover, Maine.
- U.S. Department of Energy. 1981. Development of the Strategic Plan for Industrial Energy Conservation. DOE/TIC-11112, U.S. Department of Energy, Washington, D.C.
- U.S. Department of Energy. 1981. Energy Conservation: A Route to Improved Distillation Profitability. DOE/CS-431-T1, U.S. Department of Energy, Washington, D.C.

REFERENCES AND BIBLIOGRAPHY- IRON AND STEEL

- A. D. Little, Inc. 1978. Research, Development and Demonstration for Energy Conservation, Preliminary Identification of Opportunities in Iron and Steel-making. SAN/1692-1. U.S. Department of Energy, Washington, D.C.
- Moore, J. J. June 1982. "An Examination of the New Direct Smelting Processes for Iron and Steelmaking." Journal of Metals.
- Szekely, J. February 1979. "Toward Radical Changes in Steelmaking." Technology Review. 81(4).
- Szekely, J. September 1981. "Radically Innovative Steelmaking Technologies." Metallurgical Transactions B. 11B(3).
- Tanoue, T. et al. 1981. "Coal Gasification Process of Sumitomo Metals." Presented at the International Conference on Alternative Energy Sources, December 14-16, 1981.
- Trout, H. E. September 1981. "Understanding Iron and Steelmaking Through History and Chemical Principles." Industrial Heating.

REFERENCES AND BIBLIOGRAPHY - ALUMINUM

- Aluminum Association. 1981. "Energy Conservation and the Aluminum Industry." The Aluminum Association, Washington, D.C.
- Arthur D. Little, Inc. 1979. A Survey of Potential Processes for the Manufacture of Aluminum. ANL/OEPM-79-4, Argonne National Laboratory, Argonne, Illinois.
- Forberg, H. O. April 1981. "Status and Outlook for the Aluminum Industry." Journal of Metals, pp. 48-49.
- Grjotheim, K. and J. B. See. 1979. "The Hall-Héroult Process and Alternative Processes for the Manufacture of Metallic Aluminum." Mineral Science Engineering, 2(2):81-98.
- Grjotheim, K. and B. Welch. September 1981. "Impact of Alternative Process for Aluminum Production on Energy Requirements." Journal of Metals. pp.26-32.
- Hittman Associates, Inc. 1981. Energy Conservation in the Primary Aluminum and Chlor-Alkali Industries. H-C 2112/111-81-944, Hittman Associates, Inc., Columbia, Maryland.
- Industrial Research and Development. May 1981. "Plasma Technology Used in the Production of Crude Iron." Industrial Research and Development. pp. 68-69.
- Kawahara, K. 1981. "Method of Carbothermically Producing Aluminum." Patent Application to Foreign Countries, Mitsui Alumina Co., Ltd., Tokyo, Japan.
- Marketing Perspective. April 1982. "Aluminum Cuts Watts." Design Engineering. p. 11
- Menegoz, D. C. July/August/September 1979. "New and Alternative Processes for the Manufacture of Aluminum." Industry and Environment.
- O'Hare, T. E. and F. J. Salzano. 1981. "Future Raw Materials and Energy Use in Industry - A Research Agenda." Proceedings from Workshop at Reston, Virginia, November 9-11, 1978. BNL-51382, Brookhaven National Laboratory, Upton, New York.
- Russell, A. S. 1981a. "Developments in Aluminum Smelting." Plenary Lecture at the 7th International Light Metal Congress, Vienna, June 1981, 57. Jahrg. pp. 415-419.
- Russell, A. S. 1981b. "Pitfalls and Pleasures in New Aluminum Process Development." Journal of Metals. pp. 132-137.

REFERENCES AND BIBLIOGRAPHY - CHEMICALS

- AICHE Symposium Series. 1981. "Tutorial Lectures in Electrochemical Engineering and Technology." 77(214):23-243.
- Argonne National Laboratory. 1979. A Survey of Organic Electrolytic Processes. Argonne National Laboratory, Argonne, Illinois.
- Argonne National Laboratory. 1981. Processing Engineering and Economic Evaluations of Diaphragm and Membrane Chlorine Cell Technologies. Argonne National Laboratory, Argonne, Illinois.
- Battelle-Columbus Laboratories. 1977. Developing a Maximum Energy Efficiency Target for SIC 28: Chemicals and Allied Products, Volume 6. Battelle-Columbus Labs, Columbus, Ohio.
- Beck, T. R. 1977. Improvements in Energy Efficiency of Industrial Electrochemical Processes. Electrochemical Technology Corp., Seattle, Washington.
- Beesley, A. H. and R. D. Rhinesmith. 1981. "Energy Conservation by Vapor Compression Evaporation." Aqua-Chem, Inc., CEP. pp. 37-56.
- Bojnowski, J. H. and D. L. Hanks. May 7, 1979. "Low-Energy Separation Process." Chemical Engineering.
- Burch, J. E., J. L. Otis, and R. W. Hale. 1979. Pilot Study to Select Candidates for Energy Conservation Research for the Chemical Industry. DOE/TIC-11118, Battelle-Columbus Laboratories, Columbus, Ohio.
- C&EN. December 5, 1977. "A Leap Ahead in Polyethylene Technology." pp. 21-22.
- C&EN. July 28, 1981a. "Facts and Figures for Chemical R&D." p. 37ff.
- C&EN. July 28, 1981b. "Membrane Simplify Catalytic Reactions." p. 37ff.
- C&EN. July 27, 1981a. "Science Update: Organic Chemistry." p. 38.
- C&EN. July 27, 1981b. "Visible Light Cleaves Hydrogen Sulfide." p. 41.
- C&EN. August 3, 1981a. "Supercritical Fluids Offer Improved Separations." p. 16.
- C&EN. August 31, 1981b. "Methane Reforming to Stay Key Hydrogen Source." p. 39.
- C&EN. October 5, 1981a. "Methanol Boom Will Require New Technology." p. 32.
- C&EN. October 5, 1981b. "U.S. Polymer Research May Be Declining." p.29.

C&EN. October 26, 1981c. "Fischer-Tropsch: New Life for Old Technology." pp. 22-32.

C&EN. November 2, 1981a. "French Hydrazine Process Offers High Yields." p. 32.

C&EN. November 16, 1981b. "Group to Raise Industry Funds for Campus R&D." p. 45ff.

C&EN. November 16, 1981c. "Science Update: Inorganic Chemistry." p. 42a.

C&EN. February 22, 1982. "Science Update: Polymer Chemistry." p. 36.

C&EN. March 15, 1982. "Electrolytic Cell Membrane Development Surges." p. 22.

C&EN. April 5, 1982. "Most Patents Continue to be in Chemical Field." p. 24.

C&EN. May 3, 1982a. "C&EN's Top 51 Chemical Products and Producers." p. 9ff.

C&EN. May 24, 1982b. "Balance in Innovation Involvements Being Sought." p. 9ff.

C&EN. June 14, 1982a. "Facts and Figures for the Chemical Industry." p. 31ff.

C&EN. June 21, 1982b. "Energy R&D: New Strategies Begin to Emerge." pp. 7-14.

C&EN. July 5, 1982. "Bugs and Biotechnology Breakthroughs." p. 27.

Castle Technology Corp. 1981. Survey of Electrochemical Production of Inorganic Compounds. Castle Technology Corp., Lexington, Massachusetts.

Chemical Engineering. April 23, 1979. "Crystallizer Saves Cost and Space." pp. 119-115.

Chemical Engineering. December 3, 1979. "Improved Ammonia Process." pp 88-89.

Chemical Engineering. June 28, 1982. "Will Industry Dollars Rescue University Research?"

Concentration Specialists. 1979. Investigation of Freeze Concentration as a Process for Industrial Energy Conservation in Black Liquor, Acetic Acid and Citrus Juice Applications. DOE/CS/41134-T1, Concentration Specialists, Inc., Andover, Massachusetts.

Considine, D. M., editor. 1974. Chemical and Process Technology Encyclopedia. McGraw-Hill, New York, New York.

- England, C. and J. E. Funk. 1981. "Reduction Product Yield in Chemical Processes by Second Law Effects." Energy. 5(8-9):941-947.
- Erickson, D. C. 1981. Air Separation by the Moltex Process. Energy Concepts Co., Annapolis, Maryland.
- Flynn, T. M. and J. D. Way. 1982. "Membrane Separations." Energy Progress. 2(2):79-82.
- Happer, W. et al. 1979. Laser Induces Photochemistry. SRI International, Arlington, Virginia.
- Hittman Associates, Inc. 1981. Energy Conservation in the Primary Aluminum and Chlor-Alkali Industries. Hittman Associates, Inc., Columbia, Maryland.
- International Chemical Engineering. 1981. "Energy Saving in the Chlor-Alkali Industry." 21(4):629-638.
- Joglekar, R. and R. J. Clerman. 1981. Potential Impact of Bio-Industry on Industrial Energy Consumption. Mitre Corporation, McLean, Virginia.
- Linnhoff, B. and J. A. Turner. 1981. "Simple Concepts in Process Synthesis Give Energy Savings and Elegant Designs." The Chemical Engineer. pp. 742-746.
- Lonsdale, H. K. 1982. Membrane Separation in the 1980s. Bend Research, Inc., Bend, Oregon.
- Maclean, D. L., C. E. Prince and Y. C. Chae. 1981. "Energy-Saving Modifications in Ammonia Plants." Ammonia Plant Safety. Vol. 22.
- Millington, J. P. 1975. "The Energy Efficiency of Electrochemical Processes." Chemical Industry (London), (18):781-788.
- Montedison, M. and L. Biondi. Examples of Possible Energy Savings in Chemical Industry. International Assembly of the European Federation of Chemical Engineering, November 11, 1975. Milan, Italy.
- New Mexico State University. 1981. Energy Conservation in the Petroleum and Chemistry Industry: Ammonia Process. New Mexico State University, Las Cruces, New Mexico.
- Oak Ridge National Laboratory. Industrial Energy Use Data Book, Chapter 13. Chemicals and Allied Products, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- Office of Technology Assessment. 1981. "The Chemical Industry." In Impacts of Applied Genetics. Office of Technology Assessment, Washington, D.C.
- O'Hare, T. E. and F. J. Salzano. 1981. Future Raw Materials and Energy Use in Industry: A Research Agenda. Brookhaven National Lab., Upton, New York.

- Pagani, G. and F. Granelli. May 1979. "Make Urea with Less Energy." Hydrocarbon Processing, pp. 169-172.
- Pagani, G. and U. Zardi. Ammonia Urea Integrated Process: A Contribution to the Reduction in Energy Consumption and Plant Cost. International Assembly of the European Federation of Chemical Engineering, November 11, 1975. Milan, Italy.
- Parrett, T. 1982. "Membranes, Succeeding by Separating." Technology. 2(2):16-29.
- Perry, R. H. and C. H. Chilton. 1973. Chemical Engineers Handbook. McGraw-Hill, New York, New York.
- Quillman, B. March 1981. "Synfuel Trends: Present and Future Coal Utilization at Du Pont." CEP. pp. 43-46.
- Riekert, L. December 1974. "The Efficiency of Energy Utilization in Chemical Processes." CES. 29, 1613.
- Roberts, R. et al. June 1982. Photochemistry in the Chemical Process Industries. Mitre Corp, McLean, Virginia.
- Ronn, A. M. May 1979. "Laser Chemistry." Scientific American. p. 114.
- Shreve, R. N. and J. A. Brink. 1977. Chemical Process Industries. McGraw-Hill, New York, New York.
- Stockburger, D. and L. Bartmann. 1981. "Exergetic Evaluation of the Use of Heat Pumps (Vapor Compressors) in Chemical Plants." ICE. 2(2):197-213.
- Van Gool, W. 1978. Limits to Energy Conservation in Chemical Processes. Institute for Energy Analysis, Oak Ridge, Tennessee.
- Versar, Inc. 1979. Survey of Potential Chlorine Production Processes. Versar, Inc., Springfield, Virginia.

REFERENCES AND BIBLIOGRAPHY - PETROLEUM REFINING

Chemical Engineering. October 4, 1982a. "Petroleum Refining: Bleak Now, But Brighter Days Ahead." pp. 43-47.

Chemical Engineering. October 4, 1982b. "CHEMENTATOR - Mutated Organisms are Found to be Useful in Refining Tar Sands." p. 18.

Ford, K. W. et al. 1975. "Sample Industrial Processes." American Institute of Physics Conference Proceedings No. 25, pp. 122-151, New York, New York.

Gaines, L. L. and A. M. Wolsky. 1981. Energy and Materials Flows in Petroleum Refining. ANL/CNSV-10, Argonne National Laboratory, Argonne, Illinois.

Haynes, V. O. 1976. Energy Use in Petroleum Refineries. ORNL/TM-5433, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Humphrey, J. L. 1982. "New Concepts in Hardware and Processes to Conserve Oil and Gas in Industrial Processes." Fourth Annual Industrial Energy Conservation Technology Conference, Houston, Texas.

Hydrocarbon Processing. "Refinery Capacity Grows." Gulf Publishing Company, Houston, Texas, 61(4):25.

Kenney, W. F. 1981. "Thermodynamic Analysis for Energy Conservation." 1981 Industrial Energy Conservation Technology Conference and Exhibition, Houston, Texas.

Lerner, M. O. et al. 1982. Industrial Energy Use. Prepared for Gas Research Institute by Energy and Environmental Analysis, Inc., Arlington, Virginia.

Maier, R. W. et al. 1979. Refinery Energy Profile. ORO-5262-5, Gulf Research and Development Company, Pittsburgh, Pennsylvania.

Robertson, J. L. 1982. "Energy Systems Research and Development for Petroleum Refineries." 17th IECEC Conference, Los Angeles, California.

CONTACTS - PETROLEUM REFINING

Dr. Bullin
Texas A&M University

Dennis Maloney
Exxon Research and Engineering

Frank Evans
Hydrocarbon Processing Editor

Dr. Jimmy Humphrey
ANL

Dr. Norman Li
Research Director
UOP Process Division

Dr. C. D. Holland
Texas A&M University

CONTACTS - PETROLEUM REFINING (contd)

Mr. Powers
National Petroleum Refiners

Sam Tobak
Mobil Research

REFERENCES AND BIBLIOGRAPHY- PULP AND PAPER

- Advanced Energy and Technology Associates. 1977. Energy Conservation in the Pulp and Paper Industry. Report of the Workshop on Energy Conservation in the Pulp and Paper Industry, February 1977, Dover, New Hampshire.
- American Paper Institute. 1981. Statistics of Paper, Paperboard, and Wood Pulp, 1981. American Paper Institute, New York, New York.
- American Paper Institute. 1983. A Fact Sheet on Energy in the U.S. Paper Industry. American Paper Institute, New York, New York.
- Booz-Allen and Hamilton, Inc. 1978. Development of the Strategic Plan for Federal R&D Programs in Industrial Energy Conservation. Booz-Allen and Hamilton, Inc., Washington, D.C.
- Brookhaven National Laboratory. 1978. Future Raw Materials and Energy Use in Industry - A Research Agenda. Report on a workshop sponsored by the U.S. Department of Energy, Division of Industrial Energy Conservation.
- Ceckler, W. H. 1980. DOE Wet Pressing Project Progress Report. University of Maine, Orono, Maine.
- Church, D. F. "Current and Projected Pulp and Paper Industry Problems in Process Control and Process Modeling." Crown Zellerbach Corp., Vancouver, Washington.
- Clark, J. L. et al. 1979. Energy Conservation Research in the Paper and Allied Products Industry. Prepared for U.S. Department of Energy by Georgia Institute of Technology, Atlanta, Georgia.
- Concentration Specialists, Inc. Investigation of Freeze Concentration as a Process for Industrial Energy Conservation in Black Liquor, Acetic and Citrus Juice Applications. Prepared for U.S. Department of Energy by Concentration Specialists, Inc., Andover, Maine.
- Concentration Specialists, Inc. 1981. The Use of Freeze Concentration Technology in Black Liquor Concentration. Prepared for U.S. Department of Energy by Concentration Specialists, Inc., Andover, Maine.
- Gould, R. F., editor. 1977. Cellulose and Fiber Science Developments: A World View. American Chemical Society Symposium Series, Washington, D.C.
- Hall, E. H. et al. 1975. Evaluation of the Theoretical Potential for Energy Conservation in Seven Basic Industries. Prepared for the Federal Energy Administration by Battelle-Columbus Laboratories, Columbus, Ohio.
- Hersh, H. N. 1981. Energy and Materials Flows in the Production of Pulp and Paper. Argonne National Laboratory, Argonne, Illinois.

- Hopp, W. J. et al. March 1982. Identification of Energy Conservation Research Opportunities: A Review and Synthesis of the Literature. PNL-3966, Battelle, Pacific Northwest Laboratories, Richland, Washington.
- Institute of Paper Chemistry. 1980. Development of a Cold Corrugating Process, Technical Progress Report. Prepared for the U.S. Department of Energy by the Institute of Paper Chemistry, Appleton, Wisconsin.
- Judd, M. and W. T. Kranz. 1980. High Consistency Forming Process for Paper-making, Phase I. Prepared for U.S. Department of Energy by Thermo Electron Corporation, Auburn, Massachusetts.
- Jurgensen, M. F. and J. T. Patton. 1979. Energy and Protein Production from Pulp Mill Wastes. Prepared for U.S. Department of Energy by Michigan Technological University, Houghton, Michigan.
- Jutila, E. A. et al. July 1981. "Improved Recovery Boiler Control System Reduces Energy Costs." Pulp and Paper. pp. 133-138.
- Kouvalis, A. 1977. Some Qualitative and Quantitative Information on Variations of the Kraft Process, An Energy Conservation Concept Paper. Argonne National Laboratory, Argonne, Illinois.
- Krantz, W. T. et al. 1980. High Consistency Forming Process for Papermaking, Phase II. Prepared for U.S. Department of Energy by Thermo Electron Corporation, Auburn, Massachusetts.
- Nissan, A. H., editor. March 1973. Future Technical Needs and Trends in the Paper Industry. Special Technical Association Publication, TAPPI, Atlanta, Georgia.
- Nydick, S. E. and J. B. Dunley. August 1976. Recommendations for Future Government-Sponsored Energy Conservation Research and Development in the Paper and Steel Industries. Prepared for U.S. Energy Research and Development Administration by Thermo Electron Corporation, Waltham, Massachusetts.
- Oak Ridge Associated Universities. 1980. Industrial Energy Use Data Book. Oak Ridge Associated Universities, Oak Ridge, Tennessee.
- Resource Planning Associates, Inc. 1980. Implementation of Energy Conservation Technology in the Pulp and Paper Industry. Prepared for the U.S. Department of Energy, Office of Industrial Programs, Washington, D.C.
- Richardson, D. L. and R. L. Merriam. 1977. Study of Cooling and Smelt Solidification in Black Liquor Recovery Boilers, Phase I Report. Prepared for the American Paper Institute by Arthur D. Little, Inc., Cambridge, Massachusetts.
- Rivkin, M. C. Refiner Control Strategies as an Element of Papermaking Control. Westvaco Research Laboratory, Laurel, Maryland.

- Smith, J. C. and E. L. Graminski. 1977. Characterizing the Interfiber Bonding of Paper Pulps: Effect of Preparation Pressure on Tensile Test Specimens. NBS-IR78-1459. Prepared for U.S. Department of Energy by National Bureau of Standards, Washington, D.C.
- Sobczynski, S. F. 1982. "Energy Conservation Opportunities Through Modeling and Processing Control." U.S. Department of Energy, Office of Industry Research and Development. Presented at the TAPPI Annual Meeting, Atlanta, Georgia.
- TAPPI. 1980-1982. Proceedings of the TAPPI Annual Meeting. TAPPI, Atlanta, Georgia.
- TAPPI. 1982 Issues. Journal of the Technical Association of the Pulp and Paper Industry. TAPPI, Atlanta, Georgia.
- Thermo Electron Corporation. 1976. A Study of Improved Fuel Effectiveness in the Iron and Steel and Paper and Pulp Industries. PB 254 042, Prepared for the National Science Foundation by Thermo Electron Corporation, Waltham, Massachusetts.
- Thermo Electron Corporation. 1979. Impact on Energy Conservation of Automatic Control Systems Utilization in the U.S. Pulp and Paper Industry. Prepared for the U.S. Department of Energy by Thermo Electron Corporation, Waltham, Massachusetts.
- Whetstone, J. R. and E. G. Johnson. 1981. "Sensors for Efficient Energy Utilization in the Paper Industry, Report of a Field Survey of Selected Paper Mills." National Bureau of Standards, Washington, D.C.
- Wrist, P. E. 1982. "The Direction of Production Technology Development in the 80s." Proceedings of the 1982 TAPPI Annual Meeting, Washington, D.C.

CONTACTS - PULP AND PAPER

Dr. William J. Toth
Conservation R&D Programs
EG&G Idaho

Dr. Richard Abbott
Chemical Engineering Department
University of Idaho

Dr. Arthur L. Fricke
Chemical Engineering Department
University of Maine

Dr. Peter Ariesshon
Weyerhaeuser Company

Mr. C. P. Donofrio. Director
Technical Planning and Surveillance
Champion Papers
Knightsbridge

Dr. W. Cy Rutledge
Central Research
Mead Corporation

Mr. Craig Stansbury, Manager
American Paper Institute, Inc.

Mr. Maxcy C. Rivkin
Director of Research
Westvaco Research Laboratory

CONTACTS - PULP AND PAPER (contd)

Mr. Heinz Walbaum
Manager, Process Instruments Dev.
International Paper Company
Corporate Resource Center

Mr. Robert Pfeiffer
Accuracy Corporation

Dr. Albert Co
Chemical Engineering Department
University of Maine

Mr. Stanley Sobczynski
U.S. Department of Energy

LABORATORIES VISITED

NASA Lewis Research Center
Jet Propulsion Laboratory
Oak Ridge National Laboratory
Lawrence Livermore Laboratory
Idaho National Engineering Laboratory
Sandia National Laboratory (Livermore)

REFERENCES AND BIBLIOGRAPHY - FOOD AND KINDRED

- Centec Corporation. 1981. Priority Areas for Generic Long Range Energy Related Research in the Food Industry. Prepared for the U.S. Department of Energy by Centec Corporation, Reston, Virginia.
- Miller, W. M. and E. K. Bowman. 1981. "Solid Desiccant Regeneration by Direct Solar Energy for Fresh Fruit Drying." In Agricultural Energy, Vol. 3: Food Processing. ASAE Publication 5-81.
- Randall, J. M., W. M. Camirand and H. J. Neumann. 1981. "Energy Reduction in Beet Sugar Processing by Cossette Liming." In Agricultural Energy, Vol. 3: Food Processing. ASAE Publication 5-81.
- Russell, J. H. and G. T. Tasao. 1981. "Alternative Technology for Corn Milling and High Fructose Corn Syrup Production." In Agricultural Energy, Vol. 3: Food Processing. ASAE Publication 5-81.
- University of Maryland. 1980. Sterile Acceptable Milk (SAM): A Major Energy Saving Technology. NP-2902018, University of Maryland, College Park, Maryland.
- U.S. Department of Commerce. 1980. 1977 Census of Manufacturers, Fuels and Electric Energy Consumed. MC-77-SR-4 (Part 1). U.S. Department of Commerce, Washington, D.C.
- Wheaton, F. W. et al. 1981. "Energy Requirements and Equipment for Continuous Processing of Raw Foods by Gas-Exchange." In Agricultural Energy, Vol. 3: Food Processing. ASAE Publication 5-81.

REFERENCES AND BIBLIOGRAPHY - GLASS, CEMENT AND CERAMICS

- Chiogiogi, M. 1979. Industrial Energy Conservation. Marcel Dekker, Inc., New York, New York.
- Federal Energy Administration. 1975. Energy Conservation Potential in the Cement Industry. Conservation Paper No. 26, Washington D.C. Prepared for the Federal Energy Administration by the Portland Cement Association, Portland, Oregon.
- Gordian Associates, Inc. 1974. Cement. Volume 3 of The Potential for Energy Conservation in Nine Selected Industries: The Data Base. PB-243614, National Technical Information Service, Springfield, Virginia. Prepared for Federal Energy Commission.
- Gordian Associates, Inc. 1974. Glass. Volume 7 of The Potential for Energy Conservation in Nine Selected Industries: The Data Base. PB-243618, National Technical Information Service, Springfield, Virginia. Prepared for Federal Energy Administration.
- Hopp, W. J. et al. 1981. An Overview of Energy Conservation Research Opportunities. PNL-3944, Pacific Northwest Laboratory, Richland, Washington.
- Jaegar, F. A. et al. 1978. Application of Thermal Energy Storage in the Cement Industry. CONS-5084-1, National Technical Information Service, Springfield, Virginia.
- National Materials Advisory Board (NMAB). 1980. The Status of Cement and Concrete R&D in the United States. NMAB-361, National Academy of Sciences, Washington D.C. Available from National Technical Information Service as PB80-175672.
- Oak Ridge Associated Universities. 1980. "Stone, Clay and Glass Products." Chapter 15 in Industrial Energy Use Data Book. ORAU-160, Oak Ridge Associated Universities, Oak Ridge, Tennessee.
- O'Hare, T. E. and F. J. Salzano. 1981. Future Raw Materials and Energy Use in Industry: a Research Agenda. BNL-51382, Brookhaven National Lab, Upton, New York.
- Redding, J. T. and B. P. Shepard. 1975. Energy Consumption: Paper, Stone, Clay, Concrete, and Food Industries. PB-241926, U.S. Environmental Protection Agency, Washington, D.C.
- Sapp, J. E. 1981. Energy and Materials Flows in the Cement Industry. ANL/CNSV-17, NTIS, Springfield, Virginia.
- Spellman, L. V. 1981. "The Overriding Demand for Energy Conservation in the Cement Industry." In proceedings of Industrial Energy Conservation Technology, April 26-29, Houston, Texas. Sponsored by the Energy Utilization Department of the Texas Industrial Commission.

Vaccor, J. V. and J. Jewett. 1978. Opportunities for Energy Conservation in Finished Concrete Products. HCP/CS-1549, U.S. Department of Energy, Washington D.C.

CONTACTS - GLASS, CEMENT AND CERAMICS

Mr. Gary Ganzala
Owens Corning Fiberglass
Technical Center

Mr. George McCord
Director of Project Development
Portland Cement Association

Dr. John Mooney
Director of Research
and Development
Kohler Corporation

Mr. Nate Greenie
Ideal Basic Industries, Inc.

Dr. Jay Warshawsky
Vice-President, Research
and Development
Fuller Company

REFERENCES AND BIBLIOGRAPHY - TEXTILES

- Brookstein, D. S., W. W. Carr, and W. D. Holcombe. 1979. Development and Demonstration of Energy Conserving Drying Modifications to Textile Processes Part II, Phase III. DOE/CS/41181-T2, Prepared for U.S. Department of Energy by Georgia Institute of Technology, Atlanta, Georgia, available from National Technical Information Service, Springfield, Virginia.
- Cook, F. L. et al. 1977. Energy Conservation in the Textile Industry, Phase I. ORO-5199-T1, Prepared for U.S. Department of Energy by Georgia Institute of Technology, Atlanta, Georgia, available from National Technical Information Service, Springfield, Virginia.
- Cook, F. L. et al. 1978. Energy Conservation in the Textile Industry, Phase II. ORO-5199-T2, Prepared for U.S. Department of Energy by Georgia Institute of Technology, Atlanta, Georgia, available from National Technical Information Service, Springfield, Virginia.
- Duke, M. W. 1979. Application of Foams to the Processing of Fabrics. C11-4527-4, Prepared for U.S. Department of Energy by United Merchants and Manufacturers, Langley, South Carolina, available from National Technical Information Service, Springfield, Virginia.
- Hopp, W. J. et al. 1981. An Overview of Energy Conservation Research Opportunities. PNL-3944, Pacific Northwest Laboratory, Richland, Washington.
- Oak Ridge Associated Universities. 1981. "Textiles." Chapter 11 in Industrial Energy Use in Data Book. ORAU-161, Oak Ridge Associated Universities, Oak Ridge, Tennessee.
- O'Hare, T. E. and F. S. Salzano. 1981. Future Raw Materials and Energy Use in Industry: A Research Agenda. BNL-51382, Brookhaven National Laboratory, Upton, New York, available from National Technical Information Service, Springfield, Virginia.
- Peterson, I. April 11, 1982. "Recycling Synthetic Fibers Profitably." Science News, Vol. 121.
- Washington Scientific Marketing, Inc. 1978. Report of the Proceedings of the Department of Energy Workshop on Energy Conservation in the Textile Industry. DOE/TIC-11117, prepared for U.S. Department of Energy by Washington Scientific Marketing, Inc., Washington, D.C., available from National Technical Information Service, Springfield, Virginia.

CONTACTS - TEXTILES

W. Ray Shockley
Executive Vice President
American Textiles Manufacturers

Dr. Dennis Balmforth
Institute of Textile Technology

CONTACTS - TEXTILES (contd)

Dr. Bernard Miller
Associate Director
Textile Research Institute

DISTRIBUTION

<u>No. of Copies</u>		<u>No. of Copies</u>
	<u>OFFSITE</u>	
	John Brogan U.S. Department of Energy 5E052 Office of Energy Systems Research Washington, DC 20585	Bob Mauro Industrial Applications Electric Power Research Institute 3412 Hillview Ave. Palo Alto, CA 94303
15	Marvin Gunn Energy Conversion and Utiliza- tion Technologies 1G-080 Forrestal Bldg. 1000 Independence Ave. S.W. Washington, DC 20585	Rene Abarcar Energetics, Inc. 9210 Route 108 Columbia, MD 21045
15	Jim Eberhardt Energy Conversion and Utiliza- tion Technologies 1G-080 Forrestal Bldg. 1000 Independence Ave. S.W. Washington, DC 20585	Charles Fink Energetics, Inc. 9210 Route 108 Columbia, MD 21045
27	DOE Technical Information Center Robert Holtz Argonne National Laboratory Building 330 9700 South Cass Avenue Argonne, IL 60439 Richard Silberglitt DHR, Inc. 1055 Thomas Jefferson St. N.W. Suite 414 Washington, DC 20009	Robert Vogt Industrial Utilization Gas Research Institute 8600 W. Bryn Mawr Chicago, IL 60631 Ted Willke Gas Research Institute 8600 W. Bryn Mawr Chicago, IL 60631 Howard Hagler Hagler, Bailly & Co., Inc. 2020 K Street, N.W. Suite 350 Washington, DC 20006 Martin V. Jones Impact Assessment Institute 118 Monroe St., Suite 1311 Rockville, MD 20850

No. of
Copies

Paul Massier
The Jet Propulsion Laboratory
4800 Oak Grove Drive
Mail Stop 122-123
Pasadena, CA 91103

Jovan Mocanin
The Jet Propulsion Laboratory
4800 Oak Grove Drive
Mail Stop 122-123
Pasadena, CA 91103

Yukio Nakamura
The Jet Propulsion Laboratory
4800 Oak Grove Drive
Mail Stop 502 307
Pasadena, CA 91909

Julian Szekely
Materials Science and Engineer-
ing
Massachusetts Institute of Tech-
nology
Cambridge, MA 02139

Joseph A. Carpenter
Oak Ridge National Laboratory
P.O. Box X
Building 4508 N. Room 263
Oak Ridge, TN 37830

John Gibbons
Director
Office of Technology Assessment
Congress of the United States
Washington, DC 20510

Cal Burwell
ORAU
P.O. Box 117
Oak Ridge, TN 37830

Warren Devine
ORAU
P.O. Box 117
Oak Ridge, TN 37830

No. of
Copies

Robert Williams
Center for Energy and Environ-
mental Studies
Princeton University
Princeton, NJ 08544

Dominic Monetta
Resource Alternatives, Inc.
1629 K Street, N.W.
Washington, DC 20006

Charles Berg
RFD 1
Box 2650
Buckfield, ME 04220

C. W. Robinson
Division 835Z
Sandia Laboratories
P.O. Box 969
Livermore, CA 94550

Gabor Strasser
Strasser Associates, Inc.
2616 Pine Knot Drive
Vienna, VA 22180

George Jordy
Program Analysis
U.S. Department of Energy
ER-30 A1400 GTN
Washington, DC 20545

James Kane
Basic Energy Sciences
U.S. Department of Energy
J304
Washington, DC 20545

David Klimaj
U.S. Department of Energy
CE 122
1000 Independence Avenue
Washington, DC 20585

No. of
Copies

Richard Kropschot
Basic Energy Sciences
U.S. Department of Energy
ER-10
Washington, DC 20545

Robert G. Massey
U.S. Department of Energy
CE 122
1000 Independence Avenue
Washington, DC 20585

J. Michael Power
Policy, Planning and Evaluation
U.S. Department of Energy
CE-60
Washington, DC 20585

Stanley Sobczynski
U.S. Department of Energy
CE 122
1000 Independence Avenue
Washington, DC 20585

William Thielbar
U.S. Department of Energy
Idaho Operations Office
550 Second Street
Idaho Falls, ID 83401

Marc H. Ross
Physics Department
The University of Michigan
Ann Arbor, MI 48109

Philip Schmidt
Dept. of Mechanical Engineering
University of Texas
Austin, TX

Jim Ryan
Congress of the United States
Office of Technology Assessment
Washington, DC 20510

No. of
Copies

Lee Schipper
Bldg. 90, Room 3125
Lawrence Berkeley Laboratory
Berkeley, CA 94720

Robert H. Socolow
Center of Energy and Environ-
mental Studies
Engineering Quadrangle
Princeton University
Princeton, NJ 08544

Christopher Hill
Massachusetts Institute of Tech-
nology
E40-227
Cambridge, MA 02139

Melvin Chiogiogi
Room 6A-049
1000 Independence Ave.
U.S. Department of Energy
Washington, DC 20585

Terry Levinson
Room 5E-052
1000 Independence Ave
U.S. Department of Energy
Washington, DC 20585

Kenneth Kreider
National Bureau of Standards
Physics B-250
U.S. Department of Commerce
Washington, DC 20234

OFFSITE

DOE - Richland Operations

H. E. Ransom

53 Pacific Northwest Laboratory

W. B. Ashton (10)
D. E. Blahnik

No. of
Copies

R. S. Campbell
M. Clement
K. Drumheller
D. E. Eakin
E. A. Eschbach
J. E. Garnier
W. E. Gurwell
C. R. Hahn
G. J. Hane (15)
H. Harty
S. G. Hauser

No. of
Copies

B. M. Johnson
D. R. Johnson
W. W. Laity
V. E. Lee
N. L. Moore
L. T. Pedersen
R. L. Watts
T. A. Williams
Economics Library (2)
Publishing Coordination (2)
Technical Information Files (5)