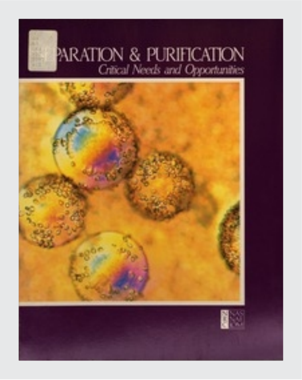

Separation & Purification: Critical Needs and Opportunities

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AUTHORS

Committee on Separation Science and Technology; Board on Chemical Sciences and Technology; Commission on Physical Sciences, Mathematics, and Resources; National Research Council

SEPARATION & PURIFICATION

Critical Needs and Opportunities

Committee on Separation Science and Technology
Board on Chemical Sciences and Technology

Commission on Physical Sciences, Mathematics, and Resources

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

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COVER: Light microscope view of human red blood cells bound to a plant lectin that is immobilized on agarose beads in an affinity chromatography column. Separations such as affinity chromatography can isolate intact cells or broken cell membranes. Photgraph courtesy of Dr. Indu Parikh, Glaxo, Inc.

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Foreword

In the fall of 1983, the Board on Chemical Sciences and Technology created the Committee on Separation Science and Technology to conduct an in-depth examination of this cross-disciplinary area, to identify opportunities for separation research to contribute to the technological needs of society, and to make recommendations to facilitate research and education.

The committee has responded to this charge by producing this report. It provides new definition to the interdisciplinary area of separations and a priority list of generic research frontiers, a marked contrast to the excessively application-specific approach often taken towards research in this area. We believe this report to be a significant contribution to providing a better foundation for future research in separations.

The Board on Chemical Sciences and Technology has carefully reviewed this report to ensure that its recommendations and priorities are consonant with those of two other major reports that have been undertaken by the board—*Opportunities in Chemistry* (1985) and a forthcoming study, *Frontiers in Chemical Engineering*, being completed by a committee chaired by Neal R. Amundson. We are satisfied that the conclusions and recommendations of the present report will not be interpreted as advocating priorities or action recommendations different from those laid out in more general terms in the disciplinary surveys of chemistry and chemical engineering.

On behalf of the Board, we wholeheartedly commend the report to the reader's attention.

Leo J. Thomas, Jr.
George M. Whitesides
Co-Chairmen, Board on Chemical Sciences and Technology

Preface

The Committee on Separation Science and Technology was organized by the National Research Council in 1983 to foster the advancement of this interdisciplinary field by defining separation problems of key importance to national technological progress, by enumerating possible approaches toward their solution, and by bringing opportunities of concern to the attention of government, industry, and academe. This report is the product of the committee's attempts to provide definition and a set of priorities to a field whose boundaries and structure are diffuse and that has lacked adequate communication and cooperation across disciplinary boundaries.

The committee has sketched out its vision of a new way of proceeding to solve separation problems—a way founded on generic research frontiers where progress will contribute to advances in many different applications of separation technology. By recasting the fundamental problems facing separation researchers and by listing them in a rough priority order, the committee hopes to stimulate research addressing the fundamental aspects of separations, and, in the process, both to engage the best minds already in the field and to attract new talent to the most significant research frontiers.

The committee has taken care to coordinate its conclusions and recommendations with several other relevant NRC reports that either have been recently issued or are in progress. These reports include *Opportunities in Chemistry* (1985) and the forthcoming *Frontiers in Chemical Engineering*. A special section discussing this overlap is included in the final chapter of the report.

I would like to thank my colleagues on the committee for their generous and very constructive efforts in bringing forth this report. The committee is particularly indebted to Dr. Elliott P. Doane of the Stauffer Chemical Company for his valuable help and advice, and to Dr. Robert M. Simon for excellent staff support. I would also like to express my appreciation to the committee's staff at the National Research Council.

C. Judson King
Chairman, Committee on Separation Science and Technology

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1

Executive Summary

THE IMPORTANCE OF SEPARATIONS TO THE UNITED STATES

Separation processes are pervasive in U.S. industry. Whether they are used to make purified products from mixtures or to remove hazardous materials from process waste streams, separations are essential to virtually all manufacturing operations in the processing industries. They are also key parts of many analytical procedures.

The efficiency of a separation process is often a major factor in determining the cost of a manufactured product. Advances in separation science and technology, therefore, are crucial to future U.S. economic competitiveness in a variety of areas, including the following ones, which are discussed in more detail in Chapter 4.

- **Biotechnology.** Most of the projected products of commercial biochemical processes are produced in dilute aqueous solution. Recovering these products from water is energy-intensive, and energy costs become a large fraction of product value in the biosynthesis of products in the price range below $10/kg. For higher value products, conventional separation systems cannot cope with the complex composition of the synthesis medium and the fragility of the biological organisms. In fact, separation systems in use today for these products are severely limited in capability and are simply scaled-up versions of laboratory analytical apparatus. Worldwide markets for these products will depend critically on development of economical and reliable manufacturing technology. Better separations are crucial to that technology.

- **Critical and Strategic Metals.** The United States is more dependent on foreign sources for critical and strategic metals, in terms of the percentage of domestic consumption that is imported, than it is for oil. This uneasy situation prevails despite the availability of dilute domestic sources for several of these metals, either in low-grade ores or in process waste materials. Research on developing efficient means of separating these metals from dilute sources can make an important contribution to U.S. national security.

- **Environment.** Many challenging enviromental problems could be ameliorated by developing and applying better separations for recovery, recycle, and reuse of waste materials. Separations used for these purposes serve directly to reduce releases of potentially toxic or hazardous materials to the environment. Examples include exhaust and stack gases, waste water, and materials that would otherwise find their ways to landfill sites or hazardous waste treatment facilities.

- **Ultrapurification.** Several "sunrise" industries have special requirements for materials of extremely high purity, where impurities must be held to levels of parts-per-million, parts-per-billion, or even less. One example is the manufacture of electronic and fiber-optic materials; the worldwide semiconductor industry currently utilizes about 4,000 metric tons of ultrapure silicon each year. Another example is the processing of food and pharmaceutical products, where potentially harmful contaminants must be reduced to very low levels. Ultrapurification of these materials calls for novel and improved methods of separation with very high selectivities.
- **Energy and Feedstocks.** The continued worldwide depletion of petroleum and natural gas reserves will generate a major need for alternate sources of energy and alternate chemical feedstocks by sometime early in the next century. Separations will necessarily play an increasingly important role in the preparation of fuels, the enhanced recovery of fuels, and the removal from fuels of contaminants that could harm the environment.

There is a common base of scientific and technological concepts underlying separations, although these concepts are at present only loosely explored and developed. A national thrust to build and expand these underpinnings is needed if the United States is to meet critical national needs and opportunities in a timely and economically efficient way.

HIGH-PRIORITY RESEARCH NEEDS AND OPPORTUNITIES

Underlying the most critical needs for improved separations are a number of generic research frontiers, where focused efforts could lead to much clearer insights into fundamental principles and major opportunities for technological innovation. Taken together, these research areas constitute a unified and coherent field of endeavor with high leverage for important national technologies. They are described in detail in Chapter 5 and are presented here in the rough priority order perceived by the committee, although advances in each of these areas will have major impacts.

- **Generating Improved Selectivity Among Solutes in Separations.** A most important generic research goal is to develop highly selective agents that can discriminate among chemically similar species in a readily reversible process. Research relevant to this goal focuses on understanding and generating separating agents with specific chemical, physical, or biological interactions at the molecular level.
- **Concentrating Solutes from Dilute Solutions.** The most promising research on better methods of concentrating dilute solutions will focus on developing agents to selectively remove solutes from dilute solutions. These agents would discriminate between solute and solvent, much as the selective agents mentioned in the preceding research area discriminate among solutes. Electrochemical, electrodialytic, and charge-mosaic processes present additional opportunities for accomplishing selective solute removal, and should be further explored. At present, concentration of solutes is most commonly achieved by removing the solvent (e.g., evaporation). For solvent removal, the most promising research areas are freeze concentration and separation processes using membranes.

- **Understanding and Controlling Interfacial Phenomena.** There are large gaps in our knowledge of phenomena at fluid-fluid and fluid-solid interfaces that affect many separation processes. A critical thrust would be the development of instrumental techniques for studying these interfaces. Other high priorities are studies of interfaces in three-phase systems; aspects of interfacial stability important in flotation, emulsion, and foams; effects of external fields on interfacial transport; and practical research on utilizing interfacial phenomena to advantage in separations.
- **Increasing the Rate and Capacity of Separations.** Emphasis should be given to means for effecting large increases in volumetric productivity and minimization of process and equipment complexity, emphasizing development of continuously staged contactors, development of high-capacity sorbents and mass separating agents, studies of hydrodynamics in process equipment, and the study of the effects of external fields on flow patterns in separations equipment.
- **Developing Improved Process Configurations for Separation Equipment.** Improved and novel separations equipment configurations should be sought. Goals include utilizing fixed beds in continuous processes, solving the problems of axial dispersion in separations equipment, developing contactors that rely on force fields other than gravity, utilizing transient and oscillating modes in separations equipment, and integrating separation operations with other process steps for greater efficiency.
- **Improving Energy Efficiency in Separation Systems.** At the systems level, continued development of heat-integration and more efficient control strategies should be pursued. Research is needed on combinations of processes to reduce energy usage for a given separation and for the regeneration of mass-separating agents.

In contrast to the basic *conceptual* unity of separation research, activities in this area are currently fragmented among many disciplines and sponsors. While there are some benefits from broad-based support and diverse programs, the current situation impairs effective communication, exchange of ideas, and technology transfer among researchers with different backgrounds. Moreover, cross-cutting research opportunities in separations often suffer when support for the field is so diffuse and oriented toward individual applications. One cogent example is the generic need for research on methods for recovering constituents selectively from dilute, usually aqueous solutions. This broad area accounts for the two highest priority research needs identified in Chapter 5, and is vitally important to three of the problem areas outlined in Chapter 4—selective recovery of products from biosynthetic and pharmaceutical fermentation processes, extraction and purification of metals from low-grade mineral resources, and removal of hazardous materials recovered from wastewater streams. There are no focused government programs of research addressing selectivity in separations or dilute-solution separations as a class, despite the clear need for fundamental research that would serve many different applications. Such research arguably would have the highest potential for stimulating commercial innovation.

The following recommendations outline an appropriate national agenda, focused on generic research and improved interactions among researchers, that will stimulate progress in the field and enable it to contribute fully to important societal and national needs.

THE NEED FOR THE FEDERAL GOVERNMENT TO STIMULATE GENERIC RESEARCH ON SEPARATIONS

Federal agencies involved in the support of research in separations should increase the focus of their activities on separations as a unified field. The committee believes that support for generic research is in no way antithetical to the need for relevance to agency missions. Indeed, generic research is often the most efficient route to progress. The committee recommends special emphasis on areas discussed in Chapter 5 and summarized in the section above.

Substantially enhanced support for generic separation research should be built on a core consisting of research support from the National Science Foundation (NSF) Separation Processes Program (in the Division of Chemical, Biological, and Thermal Engineering), the NSF Division of Chemistry, the Department of Energy (DOE) Program on Separations and Analysis, and a new initiative recommended for the National Institutes of Health. To stimulate cross-disciplinary research, the committee urges a pilot program at NSF that would be a joint undertaking between the Division of Chemistry and the Division of Chemical, Biochemical and Thermal Engineering. In mission-oriented federal agencies, including other parts of the Department of Energy, the Department of Defense, the Bureau of Mines, the Department of Agriculture, and the Environmental Protection Agency, rich opportunities exist for developing meaningful programs that respond to agency missions while advancing the field and emphasizing generic themes. Appendix B of this report contains a detailed description of existing funding of separations by federal agencies, and Chapter 6 contains an analysis of how specific agencies can respond to the opportunities that have been outlined above.

These recommendations for enhanced federal support are consistent with related and overlapping recommendations of other recent reports from the National Research Council, notably *Opportunities in Chemistry* and *Bioprocessing for the Energy-Efficient Production of Chemicals*.

PROFESSIONAL SOCIETIES AND SEPARATIONS

The fragmentation of separations research is reflected in a profusion of technical meetings dealing with specific aspects of the field, but a lack of a well-recognized, integrated, and interdisciplinary forum that can comprehensively reach those working in the areas. The very successful Gordon Research Conference on Separation and Purification and occasional Engineering Foundation Conferences reach only limited audiences.

To stimulate more effective interchange of ideas, particularly between chemists and chemical engineers, the committee urges the initiation of a Conference on Separation Science and Technology that would formally and functionally be a joint undertaking of both the American Institute of Chemical Engineers (AIChE) and the American Chemical Society (ACS). The conference would focus specifically on chemically related separations, encompassing topics that might otherwise be presented at meetings of the AIChE, of the Subdivision on Separations Science and Technology of the ACS Industrial and Engineering Chemistry Division, of the Separations Subdivision of the ACS Analytical Chemistry Division, or any of the various subject-specific meetings dealing with individual separation techniques. The conference proceedings would be published, containing peer-reviewed papers on significant research advances. There could also be in-depth reviews by leading researchers.

Such an undertaking would require a significant commitment by both professional societies, comparable to the cooperation between the AIChE and the American Society of Mechanical Engineers in organizing the National Heat Transfer Conferences. Failing the establishment of such a joint conference, the committee recommends that a new professional society for separations research be formed along the lines of the Combustion Institute.

EDUCATIONAL NEEDS

University education in separation science and technology should continue to be firmly grounded upon degree programs in the classical disciplines, notably chemical engineering, chemistry, and biochemistry.

Within chemical engineering baccalaureate programs, there should be a course emphasizing generic aspects of separations, replacing much of the content of former courses in unit operations and integrating some of the concepts currently in courses on transport phenomena and thermodynamics.

Within chemistry, it should be recognized that many aspects of classical physical chemistry underlie separation science and technology. Courses in analytical chemistry should broaden coverage to a variety of different separation methods, including, but in no way limited to, chromatographic separations. Concepts of acidity and basicity, coordination chemistry, and chelation, from advanced courses in organic and inorganic chemistry, should be built upon in the specific context of separations. A more comprehensive and generic approach to separations with biochemistry courses should be effective.

Cross-disciplinary aspects can be developed through elective interdisciplinary courses that build upon education in the classical disciplines and deal with generic aspects of separation science and technology. Focused courses dealing with more specific applications may be effective for initiating cross-disciplinary teaching activities. Graduate degrees in one discipline, following an undergraduate degree in a different discipline, afford another effective avenue.

There is a shortage of texts that can be effectively used for courses within disciplines and for interdisciplinary courses. These should follow naturally from the other activities recommended in this report.

The committee urges that the pilot program proposed above for the NSF Division of Chemical, Biochemical and Process Engineering and the NSF Division of Chemistry specifically support cross-disciplinary curriculum development in separation science and technology, in addition to research. Up to 25 percent of the funding for this program could be reserved for curriculum development. The committee also recommends establishment of a national committee that would convene and follow up on an initial interdisciplinary workshop by defining course outlines, topics, examples, and resources for interdisciplinary courses in separations, as well as for integrating generic aspects of separations into existing courses.

Because the needs for, and problems in, separation science and technology are pervasive in industry, the need for trained manpower to address these problems, both now and in the future, is great. The teaching of separations in universities should be virtually universal at the undergraduate level. At the graduate level, the committee considers it a desirable goal to have strong programs of research in separations at about half of the chemistry departments and half of the chemical engineering departments in universities nationwide. This is a considerable increase from the present level of activity. This implies that federal support of separation research must therefore be distributed broadly, rather than being concentrated at a few centers.

Continuing education affords a way of bringing recent advances in separation science and technology into practice, and for promoting well-rounded skills and interdisciplinary perspectives. The proposed joint ACS/AIChE Conference on Separation Science and Technology affords an excellent opportunity for this.

EVALUATED DATA AND PREDICTIVE MODELS

Separations research, development, and design are often hampered by a lack of reliable physicochemical data. Acquiring, evaluating, correlating, and disseminating these data should be given higher priority by the federal agencies that are concerned with separations research, comparable to the priority given to such activities as the development of specific separation applications or the development of mathematical models for separations. It is important to create more powerful predictive models for situations where experimental data on properties are lacking. The National Bureau of Standards is a logical focal point for coordinating the collection, evaluation, and dissemination of physicochemical data on separations.

CONCLUSION

The importance and pervasiveness of separations throughout the U.S. economy indicate that a federal program of generic research, of the size recommended by this committee and structured along the high-priority research frontiers identified in this report, will have significant benefits to our economic competitiveness. Although the nation is faced with a budgetary crisis of considerable magnitude, its need to address separation problems, both to meet pressing needs and to maintain international competitiveness in high-technology markets, is too great to postpone the exploitation of opportunities afforded by separation research to the indefinite future. A timely response is required if these opportunities are not to slip from our grasp.

2

Introduction

Most natural substances exist as mixtures. Separations are needed to derive specific products from these mixtures. Separations are also needed for isolating products made in the various processing industries (e.g., chemicals, fuels, pharmaceuticals, foods, and metals) and for removing contaminants from man-made wastes. They are widely used for chemical analyses of compositions of substances. Separations, and needs for separations, are pervasive.

Progress in separation research is vital for meeting several of our most critical national needs and opportunities. This fact is illustrated by the following examples.

- Successful commercialization of new concepts in biotechnology will require major reductions in the costs of isolating and purifying what are typically fragile molecules occurring as minor components of complex mixtures.
- High-technology materials, such as silicon and gallium arsenide for the electronics industry, must be refined to purity levels once thought unattainable, if they are to be used effectively.
- Obtaining critical and strategic metals such as chromium, cobalt, and nickel from low-grade sources economically requires more efficient recovery techniques than now exist. The same is true for a number of other economically important metals, including copper, uranium, and vanadium.
- Alternative fuels and alternative raw materials for the manufacture of chemicals will be needed over the next few decades. These substances will have to be isolated in an economical and environmentally acceptable manner from the complex matrixes in which they naturally occur.
- Many undesirable substances must be removed from large volumes of waste effluents to protect the environment, particularly our drinking water supply and the atmosphere.

The present and the near future are particularly important times for those areas of science and technology that focus upon separations. These needs are documented in this report. They have been recognized by a number of other recent studies, as well.[1-3]

The preceding examples also illustrate the diversity of separation applications. More than 50 different types of separation processes can be classified; these operate at feed rates that range over a factor of 10^{12}—from a few milligrams per hour to several million kilograms per hour. Given such a diverse and wide-ranging technology, one might suspect that a coherent scientific base for separations does not exist. But indeed it does, and results of fundamental research can have broad and significant applicability across many separation processes.

Concentrated efforts in the development of separations have achieved some outstanding successes in the past, particularly during World War II. In fact, the last big national "push" on separations occurred during the 1940s in response to a number of war-related emergencies. These projects included:

- the recovery and purification of the fissionable isotope of uranium for use in the Manhattan Project;
- the large-scale isolation, purification, and stabilization of penicillin (by January 1945, enough penicillin was being produced to treat approximately 250,000 wounded a month[4]); and
- the manufacture of synthetic rubber from chemical raw materials, to replace unavailable natural rubber supplies.

A retrospective look at these highly problem-specific thrusts is instructive (see Appendix C). Much of the fundamental knowledge underlying these separation applications had to be gained en route, on a very short timetable, with inefficiency, and with much extra expense. If a greater portion of the scientific base and common concepts that underlie separations had been known, progress could have been made more rapidly and efficiently. Similarly, progress on the critical current national needs and opportunities outlined above will be much more effective if a concerted push is made now to expand and develop the generic knowledge base for separations. The principal theme of this report is that such an effort is both needed and possible.

ECONOMICS OF SEPARATION

Separation processes greatly influence the cost of the material being separated. One way of illustrating this influence is by comparing the sales price of a pure substance with its original concentration in the raw material, as shown in Figure 2.1.

This plot, first formulated by Thomas K. Sherwood,[5] shows that the more dilute a substance is in its raw material, the higher its price will be, reflecting the cost of handling, transporting, and processing larger quantities of material per unit quantity of the desired product. For example, the concentration of copper in ore mined in the United States has dropped from about 3 percent in 1900 to 0.5 percent today as higher-grade ore sources have been exhausted, and costs of mining and recovery have risen accordingly.

Fortunately, improved separation technology can reduce these costs. The plot in Figure 2.1 covers many orders of magnitude. Although a factor of two in cost (about the diameter of each data point) does not look very big on such a graph, it is all-important for economic viability of a process and the market for the product. There is ample opportunity for reducing separation costs through research and innovation.

A second way of examining the cost of performing separations is to consider energy consumption. In 1979, the U.S. petroleum, chemical, and natural gas industries are estimated to have consumed about 2 quadrillion (2×10^{15}) BTUs of energy, or the equivalent of 315 million barrels of fuel oil, in performing a single separation process — distillation.[6] This energy use was greater than that of the entire U.S. commercial and general aviation industry. If fuel oil is given a crude-oil-equivalent price of $18 per barrel, two "quads" of energy cost nearly $6 billion.

Similar estimates of energy consumption are not available for other separation processes or for separations in other industries, but it is reasonable to postulate that the energy use in all other separations would at least equal that in distillation. Thus, separations most likely account for more than 5 percent of the total national energy consumption.

A third way of thinking about separation costs is to consider capital investment for separation equipment and facilities in industry. In typical chemical plants, investments in separations and supporting facilities average over one-third of the total capital cost. In petroleum refining and bioprocess facilities, the fraction may be as high as 70 percent.

Separation costs, then, are important in a number of ways, and there is a significant opportunity for reducing these costs through research and improved technology. The "Sherwood Plot" in Figure 2.1 is not a statement of immutable thermodynamic limits. In fact, most separations use more than 50 times as much energy as is thermodynamically required to perform the separation. The payoffs for improving on this low thermodynamic efficiency are so great that U.S. industry has spent a great deal of effort trying to improve specific applications of separation science and technology. It has been estimated, for example, that improvements in industrial distillation technology resulted in a savings of \$2 billion over the period 1950-1970.[7] Yet most research carried out in industry focuses, naturally, on specific separation applications. To facilitate future progress a broad effort is needed to develop the underlying knowledge base for separations. Empirical understanding of separation processes needs to be reinforced by understanding at the molecular level, new separation concepts must be devised and investigated, better integrated systems need to be designed, and research personnel must be trained and stimulated to provide these breakthroughs.

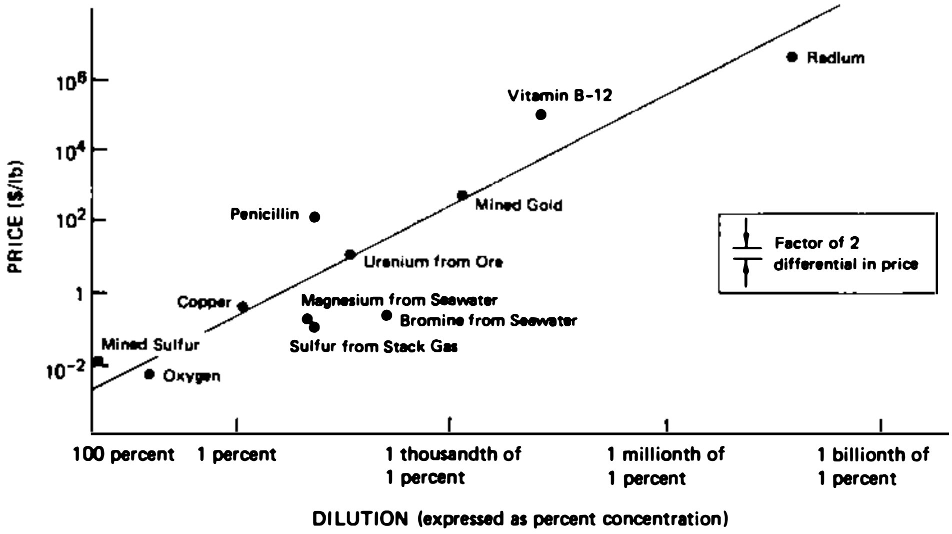


FIGURE 2.1 The Sherwood Plot: Selling prices of materials correlate with their degree of dilution in the initial matrix from which they are being separated. Note that the horizontal axis shows increasing dilution, or decreasing concentration, in the initial matrix.

[SOURCE: Norman N. Li, Allied-Signal Corporation. Modified and updated from Sherwood[5].]

STRUCTURE OF THIS REPORT

This report seeks to lay a base for such a broad effort by developing a detailed analysis of the needs, challenges, and opportunities of separations research. A more comprehensive definition and overview of separation science and technology are presented in Chapter 3. Next, Chapter 4 discusses target fields in which separation research has potentially large leverage on major technological needs. These two chapters are written for the nonexpert, to introduce the concepts and common elements underlying all separations, and to demonstrate the relevance of separation research to major societal needs.

Chapters 5 and 6 outline generic research needs and the needs of the field, respectively. In the discussion of research frontiers in Chapter 5, a more highly technical vocabulary must be used than elsewhere in the report. Recommendations from the committee on research priorities and suggested responses by federal agencies, educators, and professional societies are interspersed through the relevant text in these two chapters. These recommendations for advancing the field of separation science and technology are collected in the Executive Summary in Chapter 1 of the report.

Finally, this report contains three appendixes. Appendix A is a bibliography of key reference works in separation research, intended as an aid to investigators new to this field. Appendix B is a description of separation research programs supported by the federal government and major private consortia. Some of these programs make extramural grants to support research; others only support in-house research in federal laboratories. Because of the current uncertainty regarding federal budgets, budget data in Appendix B reflect Fiscal Year 1985 expenditures. Appendix C is a history of some past contributions of separation research.

REFERENCES

1. Commercial Biotechnology: An International Assessment, OTA-BA-218. Washington, D.C.: The Congress of the United States, Office of Technology Assessment, 1984.

2. Strategic Materials: Technologies to Reduce U.S. Import Vulnerability, OTA-ITE-248. Washington, D.C.: The Congress of the United States, Office of Technology Assessment, 1985.

3. "Report of the Research Briefing Panel on Chemical and Process Engineering for Biotechnology," in Research Briefings 1984. Washington, D.C.: National Academy Press, 1984.

4. A. J. Greene and A. J. Schmitz, Jr., "Meeting the Objective" in The History of Penicillin Production, A. L. Elder, Ed., *Chem. Eng. Prog. Symp. Ser.*, No. 100. New York: American Institute of Chemical Engineers, 1970.

5. T. K. Sherwood, "Mass Transfer Between Phases," Phi Lambda Upsilon. University Park, Pa.: Pennsylvania State University, 1959.

6. T. W. Mix, J. S. Dweck, M. Weinberg, and R. C. Armstrong, *Chem. Eng. Prog.*, 74 (4), 1978, 49.

7. F. J. Zuiderweg, *The Chemical Engineer*, No. 277, 1973, 404.

3

Separation Science and Technology: An Overview

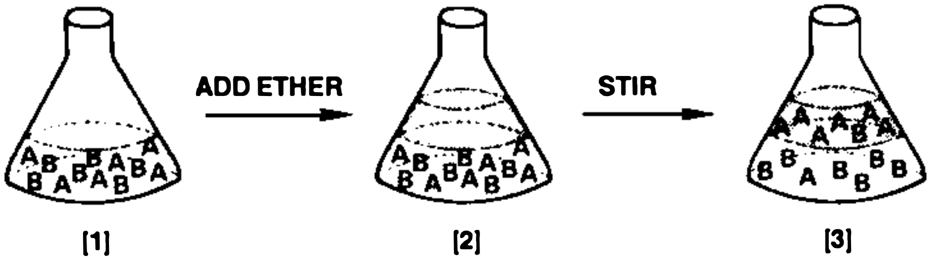
There are many different uses and types of separations, but all share common features. This brief overview defines some frequently used terms, presents some of the common aspects of separations, and categorizes some of the many and varied applications of separations into one of many possible organizational frameworks.

DEFINITIONS AND COMMON FEATURES

A few of the terms often used in describing separations serve also to show some of the common aspects among all separations.

- Every separation process divides one or more feeds into at least two products of different composition. Given a desired degree of separation, the *separation factor* (see "Solutions, Solutes, and Separation Factors" on page 13) is direct measure of how easily the separation can be made. A larger separation factor for any particular separation phenomenon results in smaller equipment and lower cost.
- All separations require *species-selective motion* in order to achieve the desired differences in composition among product streams. This is accomplished by one or more of a limited number of *separation mechanisms*.
- The basic separation provided by these fundamental mechanisms can be built upon to generate a purified product. This is typically accomplished by means such as superimposed bulk flow and/or segregation of different phases of matter or other regions differing in composition.
- Some separation processes operate on feeds that are *heterogeneous* mixtures and usually involve screening or settling. Others operate on physically *homogeneous* mixtures and must use more subtle means to create products of different composition. These latter processes are pervasive in industry, and are the principal focus of this report. They consume large amounts of energy and require sophisticated research and design.
- Separations of a physically homogeneous solution are often carried out by adding or generating a second phase and allowing the two phases to approach equilibrium. The phase that is added or generated is chosen to isolate preferentially the desired product. Such processes are called *equilibration* separation processes. The second phase is often formed by adding or subtracting energy. In distillation, for example, a vapor phase is created over a liquid phase by heating the mixture to its boiling point. In partial freezing,

SOLUTIONS, SOLUTES, AND SEPARATION FACTORS



The above illustration shows a simple separation. [1] A flask contains a solution of A and B in water. The dissolved substances, A and B, are called *solutes* and the dissolving medium, water, is called the *solvent*. [2] A second solvent, ether, is added to the flask. Since ether is only partly miscible with water it forms a separate layer, and since it is less dense than water this layer floats on top. [3] In this illustration, ether interacts with A more strongly than it does B, while water interacts with B more easily than it does A. The result is that the ether layer is rich in A, the water layer rich in B. A separation has been carried out, albeit imperfectly.

How can one express the degree of completeness of this separation? Suppose that the ether layer contains 90 percent of the A in the two-solvent system, while the water contains 80 percent of the B. The following fraction:

$$\alpha_{AB} = \frac{\text{Concentration of A in Ether/Concentration of A in Water}}{\text{Concentration of B in Ether/Concentration of B in Water}}$$

would yield the value:

$$\frac{90/10}{20/80} = 36$$

which is called the *separation factor* for the system.

The separation factor is a ratio of ratios. The numerator of the separation factor is the *distribution ratio* of A (D_A) between the two solvents, and the denominator of the separation factor is the distribution ratio of B (D_B). The larger the separation factor is, the more substance A is concentrated preferentially over B in one solvent layer. Thus, large separation factors indicate systems capable of discriminating selectively between solutes. Conversely, separation factors close to or equal to 1 are typical of systems with poor discriminating power between solutes. As an illustration, if adding the ether to the above system had resulted in no separation; if A and B had been equally present in both ether and water, the formula for α_{AB} would have yielded:

$$\frac{50/50}{50/50} = 1$$

Thus, for separations to be effective the separation factor must be different from 1. Usually A and B are chosen so that α_{AB} is greater than one. One important goal of separations research is to create separations having large values of the separation factor.

heat energy is removed from the system until one or more of the components freezes out of solution.

- In other processes, known as *rate-governed*, the difference in product compositions comes from different rates of transport of components of the mixture through a barrier or within a phase. External potentials, such as differences in temperature or electric voltage, can be imposed on such a system to create these different transport rates.
- In many processes, a material is added to form a second phase or to alter phase equilibrium or transport rates by interacting with certain components of the mixture to be separated. For example, in extraction of solids by liquids, a liquid is added that preferentially dissolves one or more constituents. To separate acids from an aqueous system, a long-chain organic amine can be added to convert the acid to the alkylammonium salt, which is preferentially soluble in an added organic phase. The material that is added to effect or enhance such separations is called a *mass separating agent*. For a process that uses a mass separating agent to be economically feasible, it is usually essential that the agent be regenerated and recycled.
- Separation processes are frequently designed so that the same basic separation is repeated several times. This design principle is known as *staging*. The two principal reasons for staging are to increase product purity beyond that provided by a single stage and to reduce energy consumption. There are two main methods of staging. *Discrete staging* involves assembling discrete but similar contactors in countercurrent or crosscurrent flow. *Continuous staging* involves equilibration across all points of the interface of two streams in countercurrent flow. In distillation these two approaches are represented by plate and packed columns, respectively.

CATEGORIZATION OF DIFFERENT SEPARATIONS

Whether used on a processing scale or for laboratory analyses, separations tend to serve one of relatively few common functions. These can be broken down into three broad and overlapping categories:

- *Concentration*, in which one or more desired substances that are dilute in a solvent or other matrix are brought to higher levels of strength within the matrix. Two important subcategories of concentration are solubilization from a solid matrix and recovery from dilute liquid solutions.
- *Purification*, in which undesired impurities are removed from a desired substance.
- *Fractionation*, in which two or more species of interest are segregated into different products.

Table 3.1 illustrates how important separation processes can be broken down into the above-mentioned categories and subcategories.

- **Solubilization from a Solid Matrix.** This class contains many of the most vexing current problems in separations, including deriving mineral values from dilute sources, more complete recovery of petroleum from underground strata, and processing of oil shale and tar sands.
- **Concentration of Dilute Solutions.** This problem is common to the recovery of chemicals made by biosynthetic processes, extraction and purification of metals, organic chemical processes involving oxidation, and the processing of effluent streams for recycling rather than release of contaminants.

- **Purification.** High-purity materials are needed as reactants in the preparation of microelectronic components and optical fibers. Ultrapurification is also needed to remove trace contaminants from some foods and drugs.
- **Fractionation.** Separating products from one another and from recycle streams is a common problem, particularly in the chemical and petroleum industries.
- **Chemical Analysis by Separation.** Separation processes are often crucial steps in analytical procedures.

Researchers in separation science and technology draw upon and contribute to the accomplishments of scientists and engineers in a variety of related fields. Analytical chemists, for example, have made major theoretical and conceptual contributions to separation research, and improved separations have played an important role in facilitating advances in analytical techniques. [See "Separations for Chemical Analysis" on page 18.] Other fields of study important to separation research include phase-equilibrium thermodynamics; mass transfer and transport phenomena in general; interfacial phenomena, including surface and colloid chemistry; mechanistic aspects of chemical reactions, especially complexation reactions; analytical chemistry; and computer-assisted process and control engineering. Future progress in separation science and technology will require continued intellectual cross-fertilization and cooperative research with scientists and engineers in these fields.

TABLE 3.1 Categories of Separation Processes

INDUSTRY	SEPARATION CATEGORY Solubilization from a Solid Matrix	 Concentration of Dilute Solutions
Biotechnology/ Pharmaceutical	Reclaiming solutes from cell mass	Recovery of products from dilute broths
Microelectronics		Recycling from effluent streams
Plastics		Removal of solvent and unreacted monomer
Metals	Leaching: underground or from tailings	Recovery of metal values from dilute leachates
Pollution Control	Removal of sulfur from coal	Recovery of sulfur from off-gases
Drinking Water Supply		
Food Processing	Extraction of beverages, e.g., coffee and tea	Concentration of fruit juices
Fossil Fuels	Enhanced oil recovery; oil from shale and tar sands	Recovery of phenols from coal-gasifier water
Nuclear Power	Selective dissolution of fuel rods	Volume reduction of radioactive waste
Commodity Chemicals	Catalyst regeneration	Recovery of ethylene glycol (antifreeze)
Fertilizers (Ammonia and Phosphate)	Extracting phosphates from rock	Handling of slimes
Pulp and Paper	Delignification	Concentration of black liquors

Purification	Fractionation	Chemical Analysis by Separation
Artificial kidney; removal of toxic impurities, e.g., antigens from penicillin	Separating product from side-products	Analyses of nutrients, toxic species, etc.
Removal of impurities from silicon, gallium arsenide, etc.	Obtaining trichlorosilane from mixed chlorosilanes	Preconcentration for analyses of reactant purity
Preparation of monomers	Separation of product polymer by molecular weight	Determining monomer purity
Removal of mineral impurities	Metals derived from common sources, e.g., Cu, Au	Selective extractants
Purification of air	Removing hydrogen sulfide from natural gas	Fractionation of PCBs
Desalinization; purification of irrigation return water		Preconcentration to allow monitoring of impurity levels
Removal of trace aflatoxins, gossypol, etc.	High-fructose corn sweeteners	Analyses of vitamins and nutrients
Removal of sulfur and nitrogen from gasoline	Separation of crude oil into streams of different boiling range	Gas and liquid chromatography
Preparation of uranium-235	Separation of short-lived waste from long-lived waste	Monitoring waste storage
Manufacture of absolute alcohol	Separation of isomers	Quality control
Purification of final product	Production of anhydrous ammonia	Monitor product purity
Removal of contaminants from effluents	Separation of pulp chemicals	Monitor effluents

SEPARATIONS FOR CHEMICAL ANALYSIS

Chemical analysis seeks to answer two questions:

- Is a particular substance present in a given sample?
- If so, how much of that substance is present?

Today, the answer to the first question is generally sought through one of a variety of spectroscopic techniques. These techniques originated in the nineteenth century with the recognition that many inorganic ions and organic functional groups absorbed specific characteristic wavelengths of incident visible or ultraviolet light and that these absorbances could signal the presence of such ions or groups in a mixture. From this beginning, there has evolved an array of spectroscopic techniques that utilize interactions of atoms and molecules with electromagnetic radiation ranging from X-rays to radiofrequency, as well as beams of electrons or ions. Although these spectroscopic techniques have wide utility for identification of constituents of mixtures, they generally do not provide precise quantitative information about the amount of a substance in a mixture, and have significant limitations for detection and analysis of substances in very dilute solutions or mixtures.

To determine accurately the quantity of a substance in a mixture, particularly when it is present in very small amount, some type of separation procedure will usually be necessary. The purpose of this separation can be to concentrate a dilute solution, to fractionate components so that they can be analyzed individually, or both. Here again, a variety of techniques have evolved for analytical separations based on differential chemical or physical behavior. Such separations can depend on phase changes solubility, volatility or differential rates of migration diffusion, electrophoresis, centrifugation.

For example, in the mass spectrometer minute quantities of a mixture can be converted into ions and ionic fragments by electron impact, and the ions then separated according to their mass/charge ratios by magnetic or electrostatic fields. Modern high-resolution mass spectrometers can determine ionic masses to an accuracy better than 1 part in 10^5, and can distinguish isomers of an organic compound by differences in their fragmentation patterns.

Chromatographic techniques were developed early in the twentieth century to separate plant pigments, by Mikhail Tswett, a Russian botanist. These techniques have played a vital role in advancing the fields of natural products chemistry, biochemistry, and molecular biology. Chromatography enables us to isolate indivudual substances from a complex mixture. "Peaks" for individual components can then be detected by an appropriate sensor. In recent years, simple chromatography has evolved into an array of techniques that depend on multistage modifications of distillation, liquid-liquid distribution, adsorption, ion exchange, and molecular sieve processes. These include gas, partition, one- and two-dimensional thin layer chromatography, and various forms of liquid chromatography (e.g., adsorption, ion exchange, gel permeation, size exclusion), which have given analysts the capability to detect minute traces of compounds in dilute and complex mixtures at high resolution.

Combination of analytical separation techniques has also become a powerful tool. For example, it is sometimes difficult to analyze the ionic fragments produced from a complex mixture in a mass spectrometer. Attaching a gas chromatograph to the sample chamber of the mass spectrometer, so that the sample is separated by the chromatograph before being analyzed by the spectrometer, gives information about identity and quantity of the individual mixture components that cannot be obtained from the spectrometer alone.

Another sophisticated form of separations analysis, one that has evolved from recent advances in biochemistry, is affinity chromatography. in this method, a specific substrate inhibitor (in the case shown in Figure 3.1, the inhibitor of enzyme A) is irreversibly attached to a solid support, where it selectively adsorbs an enzyme (enzyme A) from a complex mixture of proteins. After the unadsorbed contaminating proteins are washed away, the desired enzyme can be recovered from the affinity matrix. Qualitative or quantitative analyses of such biological mixtures are often not possible by other techniques.

As more selective analytical methods have been developed, needs have grown simultaneously for the analysis of mixtures that are both increasingly complex and increasingly dilute in the species of interest. it is now often necessary to perform a separation prior to actual analysis to remove interfering substances and to preconcentrate the species of interest. For example, solvent

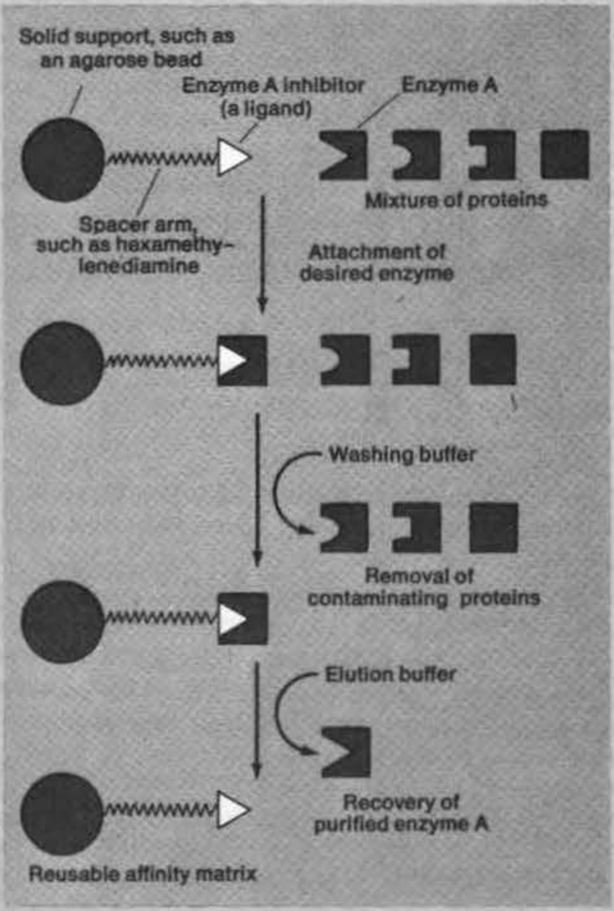


FIGURE 3.1 Steps in Affinity Chromatography.

[SOURCE: Reprinted with permission from *Chemical and Engineering News*, August 26, 1985, p. 18. Copyright (c) 1985 by the American Chemical Society.]

extraction procedures are used to preconcentrate selectively trace metal ions so that the techniques of atomic absorption spectrometry can be extended from parts in 10^9 to as low as parts in 10^{12}. Many individual constituents in body fluids and tissues can be determined by gas or liquid chromatography. Such techniques are now used routinely to monitor the molecular indications of disease and therapeutic drug levels.

Environmental pollutants can now be determined by chromatographic techniques even when the pollutant of interest is present at very low concentration in a mixture of many constituents. Thus, polychlorinated biphenyls (PCBs) can be determined routinely to parts in 10^{12}. The combination of gas chromatography and mass spectroscopy has been used to isolate and determine one specific isomer of tetrachlorodibenzodioxin in parts in 10^{15} in the presence of 21 other isomers and many other compounds in a water sample. Constituents in industrial process streams, such as those in the petrochemical industry, are routinely determined by chromatographic techniques, often with on-line systems.

There is no sign of an abatement of societal and technological pressures on analytical chemists to determine individual species at ever lower levels in increasingly complex samples. Thus the challenge continues to develop both more sensitive and selective detection instrumentation and improved separation methodology. As the frontiers of science advance, new discoveries will bring new complexities in chemical analysis that will require more highly resolving separation systems. Even now, determination of trace quantities of constituents that are of environmental, health, and technological concern often require the utmost of our present capability in separation and preconcentration. It is safe to predict that, as we continue to deal with the novel properties of high-purity materials, with the unraveling of metabolic pathways, with the detection of cancer precursors in vivo, and with the development of new materials for as yet undefined high-technology uses, the analytical chemist will be challenged to unravel complex compositional problems that will call for advanced separation concepts yet to be developed.

4

The Impact of Separation Science and Technology on Some Key Technological Challenges Facing Society

Research on separations is relevant to a number of societal problems, needs, and opportunities where technological barriers impede progress. These areas include the practical utilization of biotechnology, the dependence of the United States on imported critical metals, environmental control of pollutants, the need for ultrapurification of certain materials, and the quest for economic utilization of alternative energy resources. The opportunities that can be created by separation research in each of these areas are discussed in this chapter.

COMMERCIALIZING BIOTECHNOLOGY

Biotechnology may be defined as the practical utilization of living organisms, or portions of them, as a product or as a means of producing a desirable chemical change. Biological processes such as fermentation have been of major economic importance since prehistoric times, and the recent explosive growth in the biological sciences provides some of the most promising unexploited commercial opportunities for the remainder of this century. Estimates of potential worldwide markets for biologically derived products fall in the range of $40-100 billion annually by the year 2000.[1] A recent analysis of international competition in biotechnology[2] stresses the need for development of U.S. capabilities in the engineering of biological processes, such as separations and reactor design, in order to maintain a strong competitive position.

Biotechnology will affect the design and manufacture of a wide range of products, from diagnostic kits through pharmaceutical and agricultural products to commodity chemicals. Full exploitation of the power of biotechnology in each of these areas will be facilitated and in many cases enabled by improvements in separation technology. The importance of separations in biomanufacturing can be illustrated by the relationship between the sales price of biological products and the concentrations from which they must be isolated and purified in industrial processes (Figure 4.1). This is, of course, another form of the "Sherwood Plot" given earlier in Figure 2.1.

The relationship between cost and concentration for biological products is driven by several factors. First, bioproducts are generally produced in very dilute aqueous solutions. For the lower-cost biological products, initial volume reduction from a solution that is mostly water is an energy-intensive separation problem. In fact, for bioproducts in the price range below $10/kg, process energy costs are a large fraction of product value.

For the more costly biosynthetic products, other factors contribute to the cost-concentration relationship. High-value bioproducts are usually fragile molecules that require highly specialized and mild processing conditions. A further complication arises because these products are generally formed in complex mixtures of molecules that have similar properties. In some cases, these mixtures contain structural permutations, or *isomers*, of the desired product that differ in the subtlest of ways. (In the case of *optical isomers*, for example, the very same atoms are configured differently around a central atom. This difference between optical isomers can be detected by the way that a solution of a particular isomer interacts with polarized light.) It is often the case that only one isomer out of many possesses the biological activity that is required in an application (for example, as a drug). The ability to separate mixtures of isomers, especially optical isomers, is an important need and a major challenge.

Future separation research for biotechnology can best be discussed by focusing on three major types of biological products: analytical and diagnostic reagents, high-value substances, and commodity chemicals. Within each of these product categories, there are several possible approaches to improved large-scale separations. First, biochemical laboratory techniques for separations may be scaled up and transformed into economical processes. Second, present large-scale separations techniques from other industries may be adapted to meet the special requirements of biological applications. [See "Transferring Separation Technology: From Copper to Citric Acid" on page 24.] Finally, novel techniques may emerge from a constructive synthesis of knowledge from cell biology, biochemistry, physical chemistry, and chemical engineering.

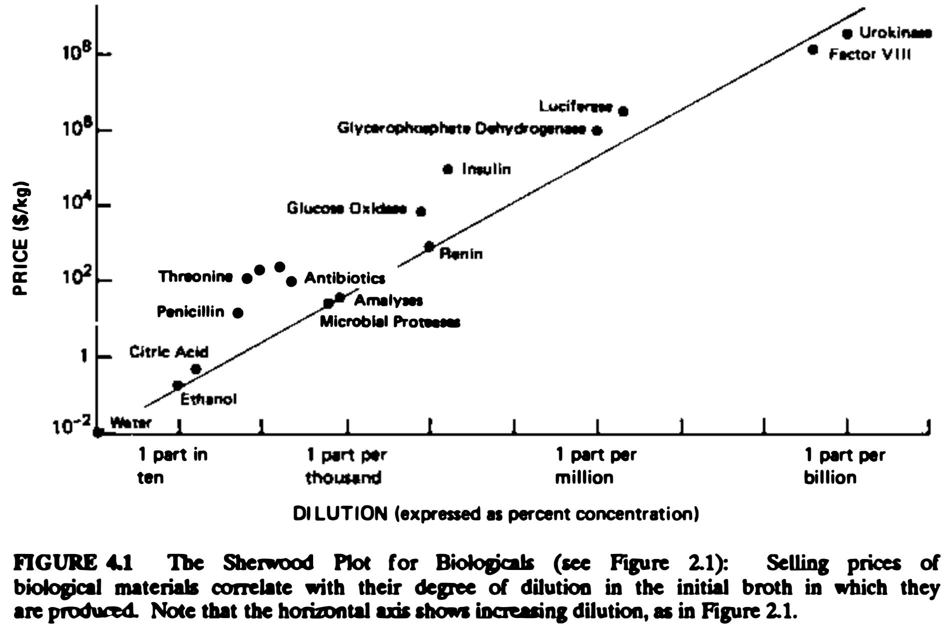


FIGURE 4.1 The Sherwood Plot for Biologicals (see Figure 2.1): Selling prices of biological materials correlate with their degree of dilution in the initial broth in which they are produced. Note that the horizontal axis shows increasing dilution, as in Figure 2.1.

[SOURCE: Norman N. Li, Allied-Signal Corporation. Modified from *Bio/Technology*, 1984, 957. Original figure copyright (c) 1984 by *Bio/Technology* and used by permission.]

Analytical and Diagnostic Reagents

Small-scale biochemical separations for medical diagnoses and process control represent a vigorously growing commercial opportunity, with additional applications in animal diagnostics, testing of food and agricultural products, and environmental monitoring. Most of the current devices in this field are simply refinements of classical analytical devices such as chromatographic columns. Rate-governed chromatographic schemes of the "field flow" type (see Figure 5.7) provide another avenue. To sustain progress in this area, fundamental research on separations is needed to provide a scientific basis for designing innovative process concepts and equipment. Some examples of research that might provide new avenues for development are as follows.

- The best chromatographs now available approach the theoretical limits of performance for conventional designs. Radical departures in design are needed to make further breakthroughs. This will require research into novel equipment configurations, better column packings, and more reliable prediction of selectivity in chromatographic separations. Also needed is a quantitative theory of such processes as gradient elution chromatography and electrophoresis.
- The development of novel nonchromatographic techniques for fractionating very large molecules, organelles, and cells is being spurred by the adaptation of separation techniques from other applications, such as elutriation, which was first developed in large settling ponds and is now being used for semimicro cell fractionation.
- New ways of designing multidimensional separations and concepts such as dielectrophoresis and magnetophoresis offer untapped opportunities.

High-Value Substances

The biosynthesis of high-value substances is one of the most exciting new opportunities in biotechnology. This class of substances includes a variety of proteins and peptides that are the focus of much interest as potentially valuable pharmaceutical agents. Some of the more tantalizing candidate compounds, and their potential uses, are listed in Table 4.1. Since most of these materials are currently needed in relatively small quantities, the key criterion for a system for isolating them from the synthesis medium is simply feasibility.

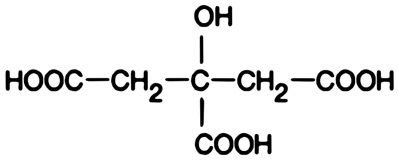
Because of the complex composition of the synthesis medium and the fragility of the products, conventional separation systems are generally not useful, and most separation systems being used today for these products are scaled-up laboratory procedures. In the future, though, some high-value substances such as tissue plasminogen activator will be required in large quantities. Other substances will become more sensitive to separation costs as competition drives prices down and makes processing costs more important. Finally, as genetically altered plant and mammalian cells are used to produce high-value substances, these exotic cells may become high-value substances themselves, and processes to separate and recycle them will have to be developed.

Separations research, then, is crucial if the United States is to develop and maintain technological leadership in manufacturing high-value bioproducts.

TRANSFERRING SEPARATION TECHNOLOGY: FROM COPPER TO CITRIC ACID

Are the concepts underlying separations really generic? Can they be transferred successfully between seemingly unrelated applications? There are a number of successful examples of just this kind of technology transfer between separation applications. This is the story of one example that has strongly influenced the technology used to produce citric acid, a 100,000 metric ton/year commodity.

Citric acid is used primarily in the food industry as an acidulant for carbonated beverages, jams, jellies, and other products. It is also used in pharmaceuticals for making citrates and effervescent salts. The citric acid molecule,



$$\mathrm{HOOC{-}CH_2{-}}\underset{\underset{\mathrm{COOH}}{|}}{\overset{\overset{\mathrm{OH}}{|}}{\mathrm{C}}}\mathrm{{-}CH_2{-}COOH}$$

contains several polar groups, and is therefore hydrophilic. It also has low volatility. In its biosynthesis by fermentation of sugar or corn syrup, it is formed in dilute aqueous solution, and the recovery of the acid from this solution is not easy. The recovery procedure traditionally used involved the following steps.[3]

- Addition of calcium hydroxide (lime) slurry to precipitate calcium citrate.
- Isolation of the calcium citrate by filtration.
- Addition of sulfuric acid to generate citric acid in a relatively concentrated aqueous solution and to precipitate calcium sulfate.
- Filtration to separate the calcium sulfate sludge.
- Recovery of crystalline citric acid by evaporative crystallization.

There were several drawbacks to this technology. First, both lime and sulfuric acid were consumed, which was expensive. Second, it was necessary to dispose of the calcium sulfate sludge. Third, the crystallization step was difficult, with low yield, because of the high concentration of calcium sulfate in the solution. Finally, impurities such as oxalic acid accompanied the citric acid through the process.

A substantial improvement in the recovery of citric acid has recently been made through the adaptation of technology originally developed for hydrometallurgical extraction. Chemically complexing extractants–chelating oximes, organophosphoric acids, and long-chain amines–have come into use on a very large scale for recovery of valuable metals–such as copper, nickel, and molybdenum–from dilute leachate solutions. Some of this technology was developed at Israel Mining Industries. These researchers subsequently became interested in the recovery of fermentation acids, and turned their attention to citric acid. Their process involves the following steps.

- Extraction of citric acid from the dilute aqueous synthesis solution by a solvent mixture composed of a long-chain tertiary amine extractant in an appropriate diluent, such as an aliphatic or aromatic solvent containing a few percent of n-octanol.[4]

- Taking advantage of the effect of temperature upon the equilibrium distribution coefficient in this system. The temperature is increased and citric acid is back-extracted from the solvent phase into the aqueous phase in substantially higher concentration than in the original fermentation solution.[5]
- Citric acid is then recovered from the aqueous solution by evaporative crystallization, in the presence of many fewer impurities than in the classical technology.

This new process has come into large-scale use because it provides for no consumption of chemicals, fewer problems of effluent disposal, and citric acid of greater purity, which facilitates subsequent crystallization and improves product quality. This successful transfer of technology from one field to another suggests that there are probably similar opportunities to develop new processes for separation, purification, and recovery of biologically produced substances and other chemicals that are synthesized in dilute solutions. However, research and development will be needed to solve the problems specific to each application.

This process is an example of a separation based upon reversible chemical complexation. This class of separations is potentially very useful for recovery of oxygenated biochemicals from aqueous solution. However, our understanding of weak, acid-base, and other complexation interactions is still rudimentary. This hampers intelligent selection of a good separating agent for a particular application. More research is needed.

TABLE 4.1 High-Value Products of Biotechnology

Product	Potential Use
Interferons	Regulation of cellular response to viral infections and cancer proliferation
Lymphokines	Modulation of immune reactions
Tissue plasminogen activator	Dissolving blood clots
Human growth hormone	Reversal of hypopituitarism in children
Neuroactive peptides	Mimicry of body's pain-controlling peptides
Regulatory peptides	Stimulation of bone and cartilage regrowth
Human serum albumin	Treatment of physical trauma
Gamma globulin	Prevention of infections
Antihemophilic factors	Treatment of hereditary bleeding disorders

TABLE 4.2 Potential Routes to Commodity Chemicals by Microbial Fermentation of Glucose

Chemical	Microrganism(s)	1981 U.S. Production (million pounds)	1981 Price (cents per lb.)
Ethanol	*Saccharomyces cerevisiae* *Zymomonas mobilis*	1,157	27.5
Butanol	*Clostridium acetobutylicum*	823	33.5
Adipic acid	*Pseudomonas* species	1,210	57
Methyl ethyl ketone	*Klebsiella pneumoniae*	62	37
Glycerol	*Saccharomyces cerevisiae* *Dunaliella* species	370	80.5
Citric acid	*Aspergillus niger*	235	77.5

[SOURCE: T.K. Ng, R.M. Busche, C.C. McDonald, and R.W.F. Hardy, *Science*, 219, 1983, 733. Copyright (c) 1983 by the AAAS. Excerpted with permission.]

A number of separation strategies used in laboratories look promising and are attractive candidates for large-scale operation:

- **Selective precipitation processes.** Precipitation techniques have been at the heart of blood plasma fractionation, and where such processes are applicable they are among the cheapest and most effective. Applying precipitation techniques to biologicals will require better understanding of both protein chemistry and fluid mechanics.
- **Separations using multiple fields.** Combinations of electrical, magnetic, and gravitational fields are beginning to be explored.
- **Membrane-based separations.** Microfiltration, ultrafiltration, and reverse osmosis are promising techniques.
- **Liquid extractions,** from both aqueous phases and nonaqueous systems.
- **Adsorptive and chromatographic separations.** As noted in the preceding section on analytical and diagnostic reagents, radically different approaches are needed to improve chromatographic separations significantly. For large-scale operations, continuous systems and high-capacity packings that are not easily crushed are needed. Concepts for new processing systems may develop from successful specialty operations such as UOP's "Sorbex" process or Exxon's magnetically stabilized moving beds of granular solids (see Figures 5.4 and 5.6 on pages 57 and 59.)

In addition to scaled-up laboratory separations, separations resulting from a creative synthesis of biochemistry, molecular biology, and chemical engineering seem particularly promising. A major problem in the separation of high-value substances is that they are generally synthesized in a dilute solution that contains other chemically similar substances. Approaches that require cooperative research between separation experts and biologists might include the following:

- genetically engineering the cell to suppress production of by-products that would complicate the separation of the desired product;
- altering the genetic structure of the cell so that the cell wall is selectively permeable to the desired product; and
- separating the desired product by one or more selective enzymatic transformations.

Commodity Chemicals

It has been predicted that biological processes will eventually offer an alternative to the current petrochemical manufacture of the organic acids and alcohols, as worldwide supplies of petroleum become more scarce and expensive. Biomass is an abundant domestic resource. While citric acid is the only commodity chemical made primarily through a biosynthetic route today, potential biological synthetic routes for a number of commodity chemicals have been demonstrated, as shown in Table 4.2. However, processing costs are, for the most part, not yet economical. Biological synthesis of any of these chemicals yields a dilute aqueous solution, and separation costs are critical to the economic success of such processes. Biological synthesis of the lower-molecular-weight commodity chemicals confronts the most serious cost problems. Their increased value relative to that of the substrate is modest, and both yield and processing cost are critically important.

For such commodity chemicals, traditional separation processes may be prohibitively expensive or impossible. For example, the distillation of a

1.5 percent solution of acetic acid in water (the maximum now attainable by fermentation) requires nearly 7 x 10^8 joules/kg of acid.[6,7] Conventional technology uses extraction followed by azeotropic distillation, which lowers the energy consumption to about 3.5 x 10^7 joules/kg of acid.[7] This is still a large figure; one that currently requires, for economical recovery of acetic acid, a minimum feed concentration of acid in the range of 3 to 5 percent. Clearly, the first step in the isolation of any of these chemicals must be a sharp reduction in the volume of the aqueous solution without a large expenditure of energy or reagents, and this volume reduction must be coupled with an economical reextraction and regeneration of any mass separating agent that has been used.

Achieving this goal will require fundamental research in a number of areas. Some promising research opportunities that extend the reach of classical separations research include the following:

- The development of more selective and higher-capacity extracting solvents, carbons, resins, and inorganic sorbents would be very useful. In particular, fundamental research on tailored sorbents, clathrates, and synthetic affinity-based adsorbents could yield important dividends.
- Research into new reversible extraction systems whose separation behavior can swing with changes in temperature, pressure, or pH seems promising. [See "Transferring Separation Technology: From Copper to Citric Acid" on page 24.] Similar approaches have been used to separate biological molecules more complex than these commodity chemicals; well-known successes include the pH-sensitive liquid-liquid extraction of penicillin and the use of ion exchange for the purification of streptomycin.
- Major advances in the prediction of parameters for phase equilibria are possible. Prediction of the properties of microporous gels, ordered open solids such as zeolites, and reversible complexation reactions would be most helpful in designing new separation process concepts.

Other promising research opportunities will emerge from a creative synthesis of separation science, reactor design, and biology. For example, fermentation products often inhibit biological processes in a feedback loop. Keeping these inhibitory products at low concentration without introducing contaminants into the fermentation that would affect its efficiency, and developing separation and fermentation processes that operate at optimal efficiency under the same conditions, are challenging, multidisciplinary problems. In the final analysis, the production of commodity chemicals using biological processes must compete economically with alternative nonbiological routes to these compounds, including the catalytic processing of synthesis gas (carbon monoxide and hydrogen mixtures). Only if energy-efficient separations can be designed will biological syntheses of commodity chemicals play a major role in the future chemical industry in the United States. And this role could be an essential part of reducing our dependence upon imported oil for chemical feedstock.

REDUCING U.S. DEPENDENCE ON IMPORTED CRITICAL METALS

Just as the United States depends heavily on foreign sources for important quantities of fossil fuels, there is an even greater dependence on foreign nations for many critical and strategic metals.[8] As with fossil fuels, this dependence has developed over a period of years as domestic high-grade sources of metals have been depleted and new foreign sources tapped. In 1978 over 90 percent of six strategic metals–niobium, manganese, tantalum, cobalt, chromium, and the platinum group metals (PGMs)–were imported, and in many cases the supplier was a politically unstable or unfriendly country.[9] Major quantities of other strategic materials are also now imported (Table 4.3), and many of those that are produced primarily in this country, including nuclear fuel materials, must use very dilute resources.

The United States is no longer a producer of the most important strategic metals (i.e., chromium, cobalt, manganese, or PGMs). The main reason for this situation is that the mineral industry cannot maintain profitable production at current prices. Policies of foreign governments to promote local economic interest, such as maintaining employment and gathering foreign currency, have also contributed to the depressed state of the U.S. mineral industry. If foreign supplies were restricted or unavailable as the result of a global or local crisis, the development of new mineral and metal separation technologies could provide for domestic production at lower cost. Therefore, in assessing the need of federal stimulation of research the primary consideration is supply security. The risks entailed in continuing to depend on foreign sources (Figure 4.2) provide an important argument in favor of stimulating research that will lead to domestic production at the lowest possible prices.

This domestic production of critical metals, facilitated by improved separation technologies, could come from four sources. The first source is the remaining domestic inventory of low-grade ores. The potential contributions to U.S. metal supplies from these reserves vary from moderate to large in the case of PGMs and cobalt, to small in the case of chromium and manganese. Several potentially exploitable PGM deposits exist, the largest of which are located in the Stillwater Complex in Montana. Potentially exploitable cobalt deposits

TABLE 4.3 U.S. Dependence on Imported Metals in 1985

	Percentage	
Niobium	100	Brazil, Canada, Thailand
Manganese	100	South Africa, France, Brazil, Gabon
Mica (sheet)	100	India, Belgium, France
Strontium	100	Mexico, Spain
Bauxite & alumina	97	Australia, Jamaica, Guinea, Surinam
Cobalt	95	Zaire, Zambia, Canada, Norway
Platinum group	92	South Africa, Great Britain, Soviet Union
Tantalum	92	Thailand, Brazil, Malaysia, Australia
Potash	77	Canada, Israel
Chromium	73	South Africa, Zimbabwe, Yugoslavia, Turkey
Tin	72	Thailand, Malaysia, Bolivia, Indonesia
Asbestos	71	Canada, South Africa
Barite	69	China, Morocco, Chile, Peru
Zinc	69	Canada, Peru, Mexico, Australia
Nickel	68	Canada, Australia, Botswana, Norway
Tungsten	68	Canada, China, Bolivia, Portugal
Silver	64	Canada, Mexico, Peru, Great Britain
Mercury	57	Spain, Algeria, Japan, Turkey
Cadmium	55	Canada, Australia, Peru, Mexico
Selenium	54	Canada, Great Britain, Japan

[SOURCE: Bureau of Mines, U.S. Department of the Interior.]

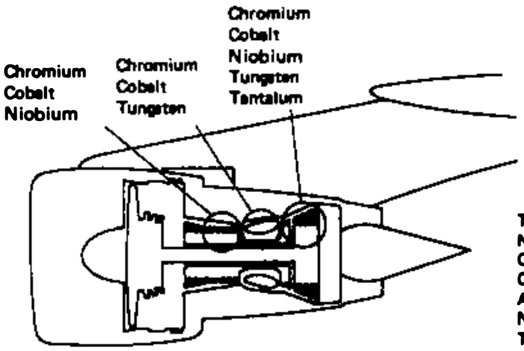
include the Blackbird Mine (Idaho), the Madison Mine (Missouri), the Gasquet Mountain Project (California), and the Duluth Gabbro Complex (Minnesota).[10] Cobalt could also be recovered together with nickel from abundant domestic laterite ores. The key to making these resources more available is basic research in extraction metallurgy.

Recycling represents a second potential source for critical metals. This may entail highly sophisticated technologies, especially in situations where the metal exists as an alloy or dilute mixture and simple recycling techniques such as mechanical segregation cannot be used. The increasing complexity of materials used in end products (e.g., jet engines and automobiles) and the general trend toward more stringent material specifications require new, technically advanced separation techniques. Extensive research in separation techniques for recycling will be needed to keep pace with changes in end products.

Process waste materials are a third potential source of critical metals. A large fraction of the domestic demand for aluminum could be satisfied if there were an economical way of recovering alumina from fly ash generated during the burning of coal.[11] Highly efficient means for recovering dissolved metals from water could be used to capture metals from process effluent streams.

Spent nuclear fuel could be a fourth source of precious metals and of reusable nuclear fuel, if appropriate, environmentally acceptable separation systems could be developed (Tables 4.4 and 4.5[12-15]). Of course, the amount of recoverable metals from this source and from process waste materials depends on the amount of material present at high enough concentration levels to make recovery economical.

Exploiting the above resources will require new techniques for extracting desired materials from very dilute sources and for separating and purifying them. In many cases, the recovery of several products from a single source will enhance the economics of such systems. Some examples of how fundamental research on separations would be of benefit are spelled out below.



Metal (lb)	U.S. dependence on foreign supplies, 1979 (%)
Titanium (5366)	100 (primary raw material)
Nickel (5204)	77
Chromium (1656)	90
Cobalt (910)	90
Aluminum (720)	10
Niobium (171)	100
Tantalum (3)	96

FIGURE 4.2 Strategic Materials in an F100 Turbofan Fighter Engine.

[SOURCE: *Mineral Processing and Technology Review*, 1, 1983, 155. Used with permission.]

- Since relatively low-grade resources will have to be used for much of the domestic metal production in the future, efficient means are needed for concentrating the crude material prior to extraction to reduce the amounts of solids handling and of extraction reagent required. Although techniques based on flotation or gravitational, magnetic, or electrostatic forces have been traditionally used for this purpose, a basic understanding of this important class of separations is lacking. Understanding particulate interactions, solid-fluid behavior, and ways of controlling surface activity is indispensable for developing better processes based on physical separations. Another promising direction is to explore the use of multiple force fields, applied simultaneously.
- New extractants with high specificities and capacities for certain metals could result in more efficient and economical recovery processes. These extractants might be solid sorbents, biosorbents, ion-exchange systems, solvent-extraction systems, or membrane transfer agents.
- The study of microbial leaching of ores and tailings by, e.g., sulfur-metabolizing organisms is another promising area of basic research.
- In situ (underground) techniques for extracting or leaching metals could become important for ore bodies that are too costly to mine and process conventionally. New, cost-effective chemical reagents for this purpose would revolutionize solution mining. While microbial slurries may be the reagents of choice for some applications, the design of environmentally benign separation reagents for solution mining is critical if such processes are to be carried out without damage to groundwater resources.

PROTECTING AND IMPROVING THE ENVIRONMENT

The expanding world population is having a tremendous impact on our ecosystem, since the environment must ultimately accommodate all human-derived

TABLE 4.4 Estimated Availability of Nonradioactive Precious Metals from Nuclear Waste in 1990

Metal	Metric Tons	Potential Value ($\$ \times 10^6$)
Rhodium-103	33	\$ 500
Palladium-106	60	\$ 900

TABLE 4.5 Radioisotopes Obtainable from Spent Nuclear Fuel

Isotope	Use
Strontium-90	Special purpose energy source
Cesium-137	Industrial radiation source

[SOURCE: Compiled by Pier R. Danesi, IAEA, from References 12-15.]

waste materials. The industries that provide us with food, energy, and shelter also introduce pollutants into the air, water, and land. The potential for an increasing environmental impact will inevitably result in society's setting ever lower allowable levels for pollutants.

The effluent streams of industry are particularly noticeable because of their large volumes. Air may be polluted with particulates such as heavy metals and hazardous organic compounds, and combustion products such as oxides of sulfur (SO_x) or nitrogen (NO_x) can contribute to acid rain. Thousands of tons of sulfur dioxide and NO_x are released into the air every day in the effluent gaseous streams from power plants and other industrial facilities.[16] Environmental concerns will undoubtedly demand that more and more of these substances be removed by separation systems.

Aqueous effluents include many types of pollutants such as particulates, droplets, or dissolved substances, and this source of pollution will increase as a synthetic fuels industry becomes extensive.[17] Isolation or recovery of such materials will be quite a challenge for innovative separation techniques.

Large quantities of solid waste generated by industry include overburden and tailings from mining, milling, and refining, as well as residues from coal-fired steam plants and the wastes from many manufacturing processes. For example, the estimated solid waste from the mining and milling industries is over 1 billion (10^9) tons per year.[18] Hazardous materials in these wastes must be removed or detoxified before the wastes can be returned to the environment. In addition, separation and recovery of primary and by-product values present in low concentrations can be made more economical by improved separations.

The nuclear industry has unique problems with radioactive wastes. Although nuclear power plants operate with less contamination of air or water than conventional electrical generating facilities, they generate solid wastes that must be carefully handled and isolated.[19] Effective ways of fractionating long-lived radioactive isotopes from short-lived ones are needed, since the long-lived ones require the most expensive handling and storage. As noted in the section on strategic metals, there may be an economic as well as environmental advantage in separating and reusing some of the components of high-level radioactive wastes prior to their disposition in acceptable repositories.

Hospitals and laboratories generate significant amounts of low-level radioactive waste. An inexpensive way of separating the small quantities of radioactive materials from these wastes would significantly benefit society by enabling use of different handling and treatment procedures for the radioactive and nonradioactive portions.

The environmental problems of residential wastes are increasing as the population grows. More than 100 million (10^8) tons of municipal solid waste is generated every year.[20] It is important to segregate and recycle useful materials from these wastes. Increased research in separations may afford new solutions to this problem. One of the best opportunities for contributions from basic research lies in the treatment of aqueous wastes, or sanitary sewage. Heavy metals, nitrates, phosphates, and dissolved carbon compounds can be present in the effluent from conventional municipal-sewage secondary treatment systems. Efficient tertiary steps are needed to separate and remove or degrade these materials to conserve our dwindling water supplies by recycling.

Finally, agriculture presents challenging pollution problems, some of which will be responsive to improved separation technology. For example, the threat to the Kesterson National Wildlife Refuge in California by drainage water with high concentrations of selenium from local agriculture illustrates the need for treating irrigation-return and other drainage water to remove potentially toxic levels of certain ions.

In many parts of the country there are no effective options for dealing with toxic liquid wastes. Landfill and surface impoundment are being phased out. There is a strong incentive toward source reduction and recycling, which, in turn, necessarily utilize separations.

All of the above separation needs for environmental considerations are oriented primarily toward removal and isolation of hazardous materials from effluent or waste streams. Pollutants are frequently present in only trace quantities, and highly resolving separation systems will be required for their detection and removal.

Separation technology is already making an important contribution to ameliorating the acid rain problem. Wet scrubbing processes are the most widely used systems for removal of sulfur and nitrogen compounds from effluent stack gases. [See "The Sulfur Problem: Where Separations Can Help" on page 34.] The limits of practicality and cost for wet scrubbing techniques, though, are such that they are not used to remove more than 75 percent of the sulfur oxide compounds present and are currently of only limited effectiveness for removal of nitrogen oxides. Such systems also produce large quantities of sludge that present a solids disposal problem. New reagent systems that can be used in a more effective recycling mode are needed, and would be particularly useful if they could simultaneously remove both sulfur and nitrogen compounds in forms from which they could be converted into useful products. Further development of solids-based processes is warranted. In any case, effective approaches must be brought into use to remove the nitrogen compounds. For power plant applications, it would also be useful to have removal systems that could operate at the temperature of the effluent as it leaves the combustion chamber, eliminating the need for reheating stack exhaust to regain buoyancy upon release.

The problem of removing pollutants from extremely dilute solutions is becoming more important as allowable release levels for pollutants are lowered. For example, proposed standards for the release of arsenic prescribe levels at or below the current limit of detection. Another example is the pervasive polynuclear aromatic hydrocarbons, some of which may be potent carcinogens. These substances have the additional complication of very low solubility in water, which promotes adsorption onto very fine suspended particles in water streams.

Three areas of separation research are particularly pertinent to these problems. One is the development of high-capacity reagent systems that are specific for certain pollutants at low concentrations. The second area is the investigation of highly efficient contacting systems to handle large volumes of effluents with minimal energy expenditure. The third important research need is for a better way of separating submicron particles suspended in large-volume streams.

It is very difficult to collect and remove such fine particles, but when this can be accomplished, separations of pollutants such as dioxin, which are strongly adsorbed onto fine particles, can be effected on a large scale. In

THE SULFUR PROBLEM: WHERE SEPARATIONS CAN HELP

Our principal sources of energy—fossil fuels—are all contaminated to some extent with sulfur compounds. When these fuels are burned, the sulfur compounds are burned to sulfur oxides, which are emitted to the atmosphere in the flue gas. In the atmosphere these oxides are converted into the sulfur acids that are a principal cause of acid rain.

When coal was the fuel that powered the industrialization of the United States in the nineteenth century, industrial centers experienced severe pollution from the emitted sulfur oxides and the sulfur acids. This pollution abated substantially with the advent of plentiful supplies of low-sulfur oil and natural gas. However, as these natural low-sulfur fuels have become depleted, sulfur pollution has returned to plague our industrial society.

Separation technology plays a critical role in limiting sulfur oxide pollution from sulfur-bearing fossil fuels. This technology is sufficiently advanced that there are no inherent technological limits to removing more than 95 percent of the sulfur present in natural gas, crude oil, and coal—a variety of processes exist for accomplishing this before, during, or after combustion. The principal barriers to nearly complete sulfur removal are cost and practicality.

Natural Gas. The principal sulfur contaminant of natural gas is another gas—hydrogen sulfide. Because hydrogen sulfide is extremely toxic, civil authorities have long forbidden significant levels of this compound in natural gas pipelines; it must be removed from the gas prior to pipeline transportation. Current separation techniques permit the safe and economical exploitation of even high-sulfur gas wells. Hydrogen sulfide is removed from natural gas by a variety of commercial processes including reaction with aqueous solutions of oxidants, absorption into aqueous solutions of bases, distillation, and selective permeation through membranes. The end product of these processes is elemental sulfur, which can be sold and, in some cases, is worth more than the co-produced natural gas. In 1984, about 24,000 tons of sulfur was produced from natural gas wells in the United States.

Petroleum. Sulfur can also be recovered from crude oil. The table below shows the approximate limits of sulfur-removal technology for different fractions of crude oil, from lightest to heaviest. This technology relies on the reaction of hydrogen with sulfur-containing compounds in crude oil (hydrodesulfurization) and permits modern refiners to turn 3 percent sulfur crudes into liquid products with no more than 0.5 percent sulfur. About 26,000 tons of saleable by-product sulfur was produced from crude oil in 1983.

Crude Oil Fraction	Boiling Range (°C)	Limit of Sulfur Remaining After Hydrodesulfurization
Naphtha Cut	< 200	Less than 1 ppm
Middle Cut	200-290	Less than 10 ppm
Vacuum Gas Oil	290-470	Less than 50 ppm
Residual Oil	> 470	About 0.5 percent

Coal. Coal can be partially desulfurized before combustion. Washing and magnetic separation are effective in reducing the content of iron sulfide, the principal inorganic sulfur contaminant, by up to 50 percent or somewhat higher. However, there are also organic sulfur compounds in coal, and a feasible means of removing them has not yet been found. Accordingly, combustion of coal produces a flue gas that contains significant amounts of sulfur oxides, which must be removed from the gas if sulfur pollution is to be minimized.

Flue gas scrubbers are proven but expensive separation devices for removing sulfur from combustion gases. For relatively small combustion units, there is the new dry scrubber technology, by which about 90 percent of the sulfur in a flue gas can be removed by contact with a lime slurry in a specially designed combination spray dryer and reactor. The reaction product is a dry calcium sulfate-sulfite mix that is environmentally benign. Larger users favor the wet scrubber technology, which is capable of removing up to 90 percent of the sulfur with a lime slurry in a contactor column. Pushing wet scrubbers to this limit is costly, though, both in terms of the amount of lime feed needed and the disposal of the sludge created.

Separation technology has made a substantial contribution to reducing the sulfur pollution problem associated with the burning of fossil fuels. The principal barrier to further alleviation of this problem is economic and will respond to improved technology gained through further research and development.

research being carried out at Dow Chemical U.S.A., concentrations of adsorbed dioxin at the part-per-quadrillion (10^{15}) level have been successfully removed from aqueous effluents. That technology has now been scaled up. Dioxin removals to less than ten parts per quadrillion are being achieved on a continuous basis on the 20 million gallon per day waste water effluent stream from Dow's Midland, Michigan, manufacturing facility.[21]

This spectacular achievement highlights an important scientific trend in analytic methodology. Analyses for pollutants at the parts-per-billion or even parts-per-trillion level are now considered routine, and even more sensitive techniques have been developed. Separation methods will be needed for concentrating trace quantities of pollutants so that instrumental methods can be used to detect and quantitate them. Complex mixtures will require high-resolution separations, probably by chromatography. The same separation concepts may also have some utility for large-scale separations. However, it should be stressed that there are practical combined economic and toxicological limits to the removal of pollutants from extremely dilute sources, even though our analytical capabilities will be able to detect even lower levels.

ACHIEVING VERY HIGH DEGREES OF PURIFICATION

There are increasing needs for carrying out separations to obtain a number of materials of extremely high purity by removing impurities down to levels of parts per million, parts per billion, and less. These needs demand special features from separation processes.

The manufacture of electronic and fiber-optic materials represents an important industry with stringent purity requirements.[22,23] The present and future uses of silicon, germanium, and gallium arsenide set purity requirements higher than have ever been met before. Figure 4.3 shows some of the starting materials used in the production of ultrapure silicon; these chlorosilanes are currently purified through distillation. The worldwide semiconductor industry currently uses about 4000 metric tons of ultrapure silicon per year, worth many

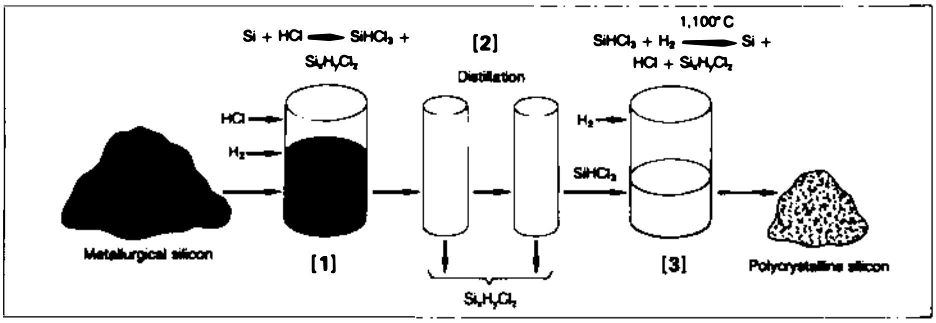


FIGURE 4.3 Manufacture of Ultrapure Silicon: The production of polycrystalline silicon for the electronics industry involves several steps aimed at the reduction of impurities. These include [1] the reaction of metallurgical grade silicon to produce a mixture of chlorosilanes, [2] distillation of trichlorosilane, and [3] reduction of trichlorosilane to polycrystalline silicon.

[SOURCE: Excerpted by special permission from *Chemical Engineering* (June 10, 1985). Copyright (c) 1985, by McGraw-Hill, Inc., New York, NY 10020.]

thousand dollars per metric ton. This quantity could increase manyfold with large-scale use of semiconductor materials for photovoltaics or solar photochemistry. Ultrapurification of these semiconductor materials calls for development of novel and improved methods of separation with very high selectivities. Zone refining, which is based upon the high selectivities attainable in crystallization processes, is a successful example of such a development. Because of the many different situations that are encountered, we need more processes of this sort, capable of scale-up and reliable, continuous operation.

The electronics industry also requires separations to create particle-free clean rooms of the order of 10 particles per cubic foot (350 per cubic meter) greater than 0.2 micron in size. Future requirements for clean rooms may be of the order of 1 particle per cubic foot (35 per cubic meter) or less (Figure 4.4).

Another industry with strict demands for purity is the food processing industry. Several food processing applications require the removal of specific substances to very low levels. An example is the removal of residues of chlorinated solvents used for decaffeination of coffee. In addition, many pharmaceutical products require high degrees of purification to remove undesirable biologically active substances.

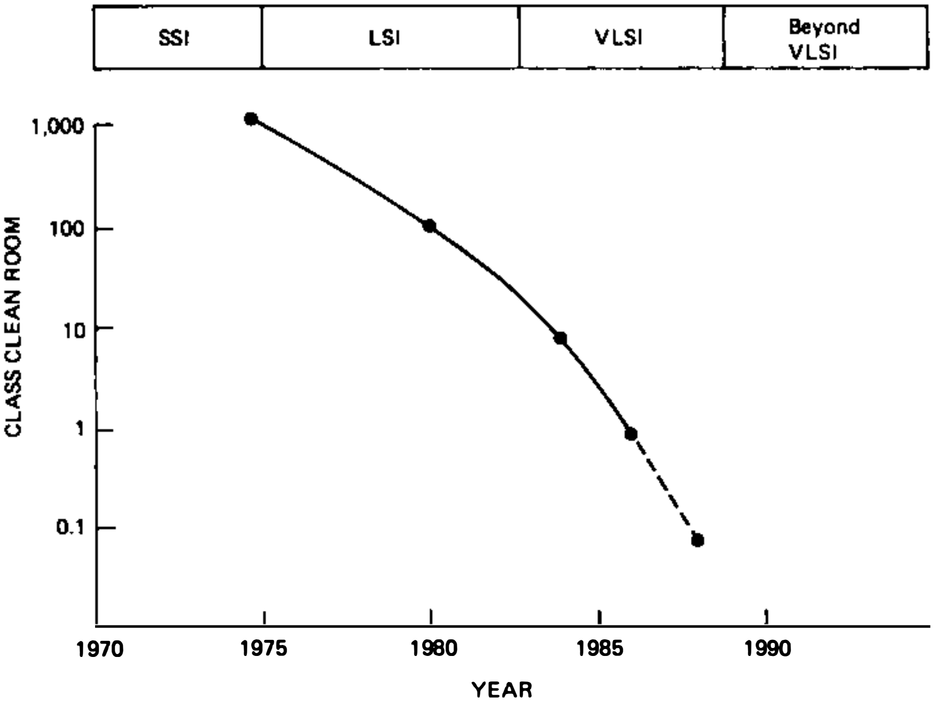


FIGURE 4.4 Trends in Requirements for Clean Rooms: Clean room classes are defined by the maximum number of particles greater than 0.2 microns in diameter that are allowed per cubic foot of air. As the design of integrated circuits has evolved from small-scale integration (SSI) to beyond very-large-scale integration (VLSI), the sensitivity of the manufacturing process to impurities in the surrounding air has increased. The requirements for clean rooms where manufacturing processes are carried out have become increasingly more stringent.

[SOURCE: Isaac Trachtenberg, University of Texas, Austin]

A related application for ultrapurification can be found in the area of biological and toxicological testing. In order for such tests to yield valid results, candidate compounds must be free of all impurities that could affect the test. A final need for ultrapurification is represented by the entire area of reprocessing hazardous wastes. This need has already been partly explored in the preceding section on "Protecting and Improving the Environment." The need to remove dioxins from contaminated soils at certain Superfund waste sites, down to parts-per-trillion or parts-per-quadrillion levels, is an example of an ultrapurification problem on a massive scale. The development of fully demonstrated and accepted decontamination techniques for hazardous waste sites is needed to use Superfund appropriations effectively and efficiently.

Ultrapurification cannot be achieved practically unless one is able to analyze chemically for specific impurities at very low concentrations and to understand the implications of the data that such analyses provide. Satisfying the need for ultratrace detection requires sophisticated techniques for preconcentrating impurities before analysis techniques capable of both high degrees of concentration and nearly complete recovery of the substances of interest. These preconcentration methods also require their own set of ultrapure reagents and solvents. Otherwise, the ultimate analysis may be dominated by impurities introduced during the preconcentration. This need can call for removal of impurities in solvents and reagents to very low levels, approaching or exceeding the limit of detection. Another important problem in ultratrace analysis is raised when trace substances occur in a chemically sequestered form; for example, in complexes with other solutes or incorporated into micelles. This sequestering complicates trace substance removal and detection. Basic separations research, focused on complexation chemistry, may provide a solution to this problem.

Facilitating determination of ultratrace impurities through better separation methods will have several important benefits. One will be to lower the cost and increase the reliability of biological and toxicological testing. Another benefit will be to improve manufacturing quality for chemical and biological products. In manufacturing processes, improved separations will facilitate the development of better on-line monitors that could be used as a portion of the process control loop.

DEVELOPING ALTERNATIVE ENERGY SOURCES AND RESOURCES FOR CHEMICALS

The continuing depletion of fossil fuels, especially conventional liquid and gaseous fuels, is expected to create a need for alternative sources of energy in coming decades. The need will not be just for energy itself, but for energy in convenient and environmentally acceptable forms such as electricity, or liquid and gaseous fuels that can be easily stored and transported. Although nuclear sources and conventional fossil fuels will continue to be important components of our future energy supply, alternative sources of energy will also be required as some fossil fuels become scarce and energy demands increase.

A more complex mix of energy sources may be required to meet these needs. For instance, fusion may ultimately become a primary process for the production of electricity, although it will not be a source of liquid or gaseous fuels. On the other hand, renewable energy sources such as biomass may be used for liquid and gaseous fuels. Some of the alternative energy sources currently viewed with considerable hope are tertiary oil recovery; oil shale and tar sands as sources of hydrocarbon feed stocks; conversion of coal to liquid and gaseous fuels; biomass as a renewable fuel or feed material for liquid and gaseous fuels; and fusion energy to augment the production of electricity. Separations will play an important role in the preparation of fuels, the recovery of unused fuels, and in the removal from effluents of contaminants that could harm the environment.

Tertiary oil recovery represents a potential source of hydrocarbon fuels that is just beginning to have an important impact.[24] The potential resource is huge since conventional recovery techniques may leave 50 percent or more of the oil in the ground. Tertiary recovery methods currently under development involve the injection of fluids into oil-bearing formations to cause hydraulic fracture, thus making the oil more accessible, or the injection of chemicals such as carbon dioxide or surfactants to facilitate the removal of the oil. The mechanisms of separation of the oil from a porous matrix have not been well-defined, and economical recovery of some of the possible additives has not been established.

Several separation problems can be identified in the recovery of hydrocarbons from shale and tar sands.[25,26] In both cases the fossil resources are contained at relatively low concentrations in a solid matrix. Most research has been directed toward the recovery of oil by heating. In the case of shale, the heat is usually provided by partial combustion of the shale, producing gaseous and liquid products that must be separated and refined to produce usable fuels.

Coal, one of our most abundant fossil fuels, is conventionally burned to produce steam or heat, but it can also be used as the feed material for the production of liquid or gaseous fuels. Strictly speaking, this is not an alternative energy source, but an alternative energy form. Heating coal in the presence of a catalyst converts it directly into liquid and gaseous fuels and a char residue. Gasification of the char to synthesis gas (carbon monoxide and hydrogen) can be carried out; synthesis gas can then be converted to liquid or gaseous fuels. Synthesis gas can also be produced directly by coal gasification or by reaction of coal with steam.

The processing steps for treating coal-conversion liquids are similar to those used in oil refineries, although they may differ in detail because the coal liquids contain more aromatic compounds than most crude oils currently processed. Some special needs for new developments in separations can be outlined. For example, some of the compounds present in coal liquids are toxic and must be removed before the fuel is marketed. In addition, coal liquids can be heavily contaminated by fine particles which must be removed. Solvent extraction or sorption systems may be the best separation techniques for some of these problems, but separation reagents and mechanisms for coal liquids are not well developed.

The products and effluents of coal gasification may require processing at extreme conditions (e.g., clean-up at high temperature and pressure prior to use as a turbine fuel). Separation systems that can operate at these extreme conditions will be required. The principal contaminants to be removed from gaseous fuels are inert products that would diminish the energy content of the fuel, fine particles, and corrosive chemicals.

The use of biomass or biomass wastes as an alternative energy source involves growing and harvesting plants that contain significant amounts of fixed carbon and either subsequent combustion for heat or conversion of the plant material to other fuels. The conversion can involve the production of fluid fuels, e.g., fermentation to an alcohol, anaerobic digestion to gaseous hydrocarbons (principally methane), or thermolysis to a char that can be converted into synthesis gas. Fermentation produces dilute products that must be concentrated for use as fuel. Anaerobic digestion of biomass produces methane contaminated with carbon dioxide, hydrogen sulfide, and other gases that must be removed because they lower the heating value of the fuel or are toxic.

Energy efficiency is a common issue in separation research on alternative energy systems that produce liquid or gaseous fuels. The fuel values must be reclaimed from more dilute sources (tertiary oil recovery, shale, and biomass) or from chemical forms that are different from and more complex than conventional sources (coal conversion, shale, and tar sands). Greater use of low-energy separation methods will be required.

Fusion energy is an alternative energy form that does not depend upon our limited supplies of fossil fuel materials. It offers the potential for providing the large concentrated electric power sources needed for large industrial facilities. Separation systems will be necessary for the initial isolation of fuel (deuterium oxide) from natural water sources, for recycling "unburned" deuterium and tritium from fusion plasma exhaust systems, and for recovering tritium bred in fusion reactor blankets and present in the coolant and gaseous exhausts. The potential environmental impact of tritium is a concern.[27] It is highly toxic and can permeate metal walls and most containment systems, thus contaminating the coolant (which will probably be water) and spreading throughout the reactor system. Clearly, novel separation concepts will have to be developed to meet this problem before fusion reactors can be designed and built safely. Since deuterium and tritium condense into a liquid only at extremely cold temperatures, it is likely that separation processes for them will involve efficient adsorption systems operating at cryogenic conditions, or will take advantage of differences in chemical reactivity. Fundamental understanding of these types of separation system is lacking.

The use of alternative fuel sources will depend heavily on advances in separations that provide for fuel preparation and amelioration of potential environmental impacts, while consuming relatively little energy. This area, like the others that have preceded it in this chapter, poses difficult challenges to the ingenuity and resourcefulness of scientists and engineers. How can a program of basic research begin to address these critical needs? This question is addressed in the following chapter on generic research in separations.

REFERENCES

Commercializing Biotechnology

1. "Report of the Research Briefing Panel on Chemical and Process Engineering for Biotechnology," p. 31, in Research Briefings 1984. Washington, D.C.: National Academy Press, 1984.

2. Commercial Biotechnology: An International Assessment, OTA-BA-218. Washington, D.C.: The Congress of the United States, Office of Technology Assessment, 1984.

3. R. N. Shreve and J. A. Brink, Jr., Chemical Process Industries, 4th ed., p. 541-542. New York: McGraw-Hill, 1977.

4. E. F. Bouchard and E. G. Merritt, "Citric Acid," in Kirk-Othmer Encyclopedia of Chemical Technology, 3rd ed., Vol. 6, p. 150. New York: Wiley-Interscience, 1979.

5. A. M. Baniel, R. Blumberg, and K. Hajdu. U.S. Patent 4,275,234. June 23, 1981.

6. T. K. Ng, R. M. Busche, C. C. McDonald, and R. W. F. Hardy, *Science*, 219, 1983, 733.

7. R. M. Busche, *Biotech. Prog.*, 1, 1985, 165.

Reducing U.S. Dependence on Imported Critical Metals

8. (a) Minerals and Materials, A Monthly Supply, June 1980. Washington, D.C.: Bureau of Mines, U.S. Department of the Interior, 1980.

   (b) Strategic and Critical Non-Fuel Minerals: Problems and Policy Alternatives. Washington, D.C.: The Congress of the United States, Congressional Budget Office, 1983.

9. A. Maimoni and I. Y. Borg, *Min. Proc. and Tech. Rev.*, 1, 1983, 155.

10. Strategic Materials: Technologies to Reduce U.S. Import Vulnerability, OTA-ITE-248. Washington, D.C.: The Congress of the United States, Office of Technology Assessment, 1985.

11. J. G. Morse, *Min. Energy Res.*, 23(5), 1980, 1.

12. F. J. Smith and H. F. McDuffie, *Sep. Sci. Tech.*, 16, 1981, 1071.

13. F. P. Roberts, "The Radiation Characteristics of Reactor Produced Rhodium, Palladium, Ruthenium, and Technetium," BNWL-1693. Richland, Wash.: Battelle Pacific Northwest Laboratories, 1972.

14. L. L. Clark, F. P. Roberts, and J. C. Sheppard, "A Market Analysis of the Fission Product, Rh, Pd, Ru, and Tc," BNWL-1690. Richland, Wash.: Battelle Pacific Northwest Laboratories, 1973.

15. H. F. McDuffie, "Recovery of Nonradioactive Palladium and Rhodium from High-Level Radioactive Wastes," ONRL/TM-6654. Oak Ridge, Tenn.: Oak Ridge National Laboratory, 1979.

Protecting and Improving the Environment

16. T. F. Lowery, et al., "Formation and Regional Accumulation of Sulfate Concentrations in the Northeastern United States," in Environmental and Climatic Impact of Coal Utilization, J. J. Singh and A. Dupak, Eds. New York: Academic Press, 1980.

17. R. G. Luthy, *J. Water Poll. Control Fed.*, 53, 1981, 325.

18. Minerals Yearbook 1983, Vol. 1, p. 9-14. Washington, D.C.: Bureau of Mines, U.S. Department of the Interior, 1984.

19. J. W. Phillips and J. Gruhlke, "Summary of Radioactivity Released in Effluents from 1973 to 1976," EPA 520/3-77-012, p. 1. Washington, D.C.: U.S. Environmental Protection Agency, 1977.

20. Materials and Energy from Municipal Waste. Washington, D.C.: The Congress of the United States, Office of Technology Assessment, 1978.

21. G. R. Veurink, Dow Chemical U.S.A., private communication, 1986.

Achieving Very High Degrees of Purification

22. T. Abe, K. Kikuchi, S. Shirai, and S. Muraoka, "Impurities in Silicon Single Crystals: A Current View," in Semiconductor Silicon 1981, H. R. Huff, Ed., *Proceedings Electrochem. Soc.*, 81(5), 1981.

23. G. D. Larrabee, *Chem. Eng.*, June 10, 1985, 51.

Developing Alternative Energy Sources and Resources

24. B. Linville, et al., "Projects and Supporting Research on Enhanced Oil Recovery and Improved Drilling Technology. Progress Review Number 32: Quarter Ending September 30, 1982," DOE/BETC-82/4. Washington, D.C.: U.S. Department of Energy, 1983.

25. Toward a Definition of Tar Sands: Proceedings of Energy from Tar-Sand Workshop, Reston, Va., August 7, 1980. Washington, D.C.: U.S. Department of Energy, 1980.

26. An Assessment of Oil Shale Technologies. Washington, D.C.: The Congress of the United States, Office of Technology Assessment, 1980.

27. J. B. Cannon, et al., "Background Information and Technical Basis for Assessment of Environmental Implications of Magnetic Fusion Energy," DOE/ER-0170. Washington, D.C.: U.S. Department of Energy, 1983.

5

Generic Research Frontiers

The previous chapter discussed the potential impact of separation research on a number of our nation's and society's needs and the potentially large payoff that could result from fundamental research in separation science and technology. However, a federal program to expand the base of scientific and technical knowledge concerning separations would be poorly conceived if it was simply structured along impact-oriented lines. The keys to improved separations are generic; they cut across many applications. A federal program that would enlarge the knowledge base underlying separations must define and focus on generic themes. This committee offers six such themes with a discussion of significant research directions typified by each one. These themes are presented in rough order of perceived importance by the committee. They are as follows:

- generating improved selectivity among solutes in separations;
- concentrating solutes from dilute solutions;
- understanding and controlling interfacial phenomena;
- increasing the rate and capacity of separation systems;
- developing improved process configurations for separation equipment; and
- improving energy efficiency in separation systems.

> **Summary Recommendation:** Underlying the most critical needs for improved separations are six generic research areas, where focused efforts will lead to clearer insights into fundamental principles and major opportunities for technological innovation. These generic research areas should be the basis for a coherent national program on separation research.

GENERATING IMPROVED SELECTIVITY AMONG SOLUTES IN SEPARATIONS

Ideal separations, where two or more substances are completely separated from one another, are never achieved in practice for homogeneous solutions. In fact, a law of diminishing returns applies, whereby it becomes more and more expensive to achieve greater degrees of separation among substances. As one example, achieving more nearly complete separations between two products by distillation requires equipment that contains more stages (or plates), and which therefore costs more.

Since, as noted at the beginning of Chapter 3, separations of homogeneous solutions pervade the chemical and allied processing industries and consume much energy, it is important to find ways of obtaining greater degrees of separation within a simple separator. This can be accomplished by increasing the separation factor.

For those processes that use a mass separating agent (e.g., a solvent, a sorbent, a membrane), the separation factor increases with increasing selectivity of the mass separating agent. It is critically important to seek and develop highly selective separating agents. Often it is necessary to fractionate among two or more substances present as solutes in solution. A selective separating agent will interact much more strongly with some of these substances or solutes than with the others.

Mass separating agents should be *regenerable*. They should be designed so that the substances or solutes with which they interact can be recovered from them without a large expenditure for equipment or energy. Thus, the interaction between the separating agent and the substances taken up needs to be reversible. This implies that the interactions between mass separating agents and solutes should have an association energy that falls between those observed for ordinary van der Waals interactions and those observed for full chemical reactions (Figure 5.1). This is the world of coordination chemistry, dominated by complexation, or association, reactions.

Research on separating agents with high selectivity should focus on fundamental interactions at the atomic or molecular level and on ways in which

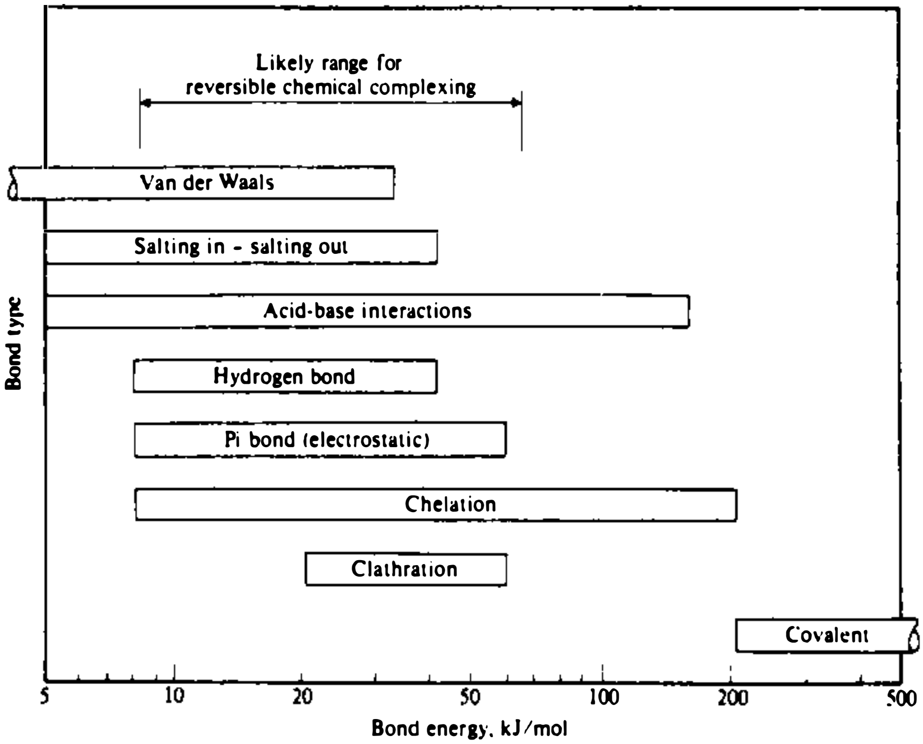


FIGURE 5.1 Bond Energies Most Suited for Chemical-Complexing Processes.

[SOURCE: Excerpted by special permission from Separation Processes, 2nd Ed., 1980, p. 737. Copyright (c) 1980, by McGraw-Hill, Inc., New York, NY 10020.]

chemical, physical, and biological phenomena can be used to enhance selectivity of mass separating agents and membranes. A key requirement for progress is a better understanding of intermolecular interactions in highly nonideal liquid solutions and between solutes and various extractants, sorbents, and other selective agents. Thermodynamic data (e.g., enthalpies, entropies, free energies) are particularly needed.

Research on improving selectivity currently focuses on relatively few areas, such as the use of crown ethers, laser excitation, and extraction with supercritical solvents. Each of these methods has limitations, and a major initiative to increase support for research on improving selectivity should be directed to a much wider variety of approaches.

Chemical Interactions

Reversible complexation reactions offer many opportunities for gaining the high specificity needed to make separations more economical. Such reactions include hydrogen bonding, acid-base reactions, electron donor-acceptor interactions, clathration, and chelation. These reactions can be used to enhance many types of separation processes, including solvent extraction, gas adsorption, extractive distillation, and enhanced-transport membrane processes. Exploring these reactions and utilizing them in processes offer fertile ground for interdisciplinary research between chemists and chemical engineers.

For example, reagents that can form inclusion complexes offer possibilities for effecting separations based on molecular size. Such inclusion complexes arise when one stable compound combines with another without the existence of substantial chemical bonds between the two components. This is possible if one of the compounds can form a very open structure containing cavities, holes, or channels in which atoms or molecules of the other can be trapped. These inclusion complexes, or *clathrates*, are capable of separating molecules based on differences in size and shape. Other compounds, while not classifiable as clathrates, afford similar possibilities for separations based on geometric factors. Graphite and other materials that have layered crystal structures can form intercalation compounds that discriminate on the basis of shape. The crystal structure of urea, for example, has parallel uniform capillaries; it has been used to separate straight-chain hydrocarbons from branched ones, the latter being unable to fit into the capillaries. Molecular sieves can carry out size-based separations governed by the diameters of very uniform holes of molecular size. Recent extensions of the use of inclusion phenomena in separations are illustrated by work being carried out on liquid inclusion compounds and on separation achieved with micelles and reverse micelles.

The power of modern synthetic chemistry, in conjunction with separation science, can be used to create new separating agents with enhanced functionalities for selective separations. These agents can take several forms. Synthetic polymer chemistry can be used to develop new sorbents and membranes. Reagents that can form inclusion compounds can also be tailored through elegant synthetic chemistry. The separation of optical isomers is even possible, given the careful design of chiral cavities in molecular sieves and the host compounds for inclusion complexes.

Chemical synthesis is already being used to enhance the selectivity of separating agents by incorporating steric factors into designs that are based on a selective chemical reaction. One example of this development is illustrated by the use of large, bulky substituent groups on amines utilized for acid gas treatment (Figure 5.2). The conventional amine reacts with carbon dioxide to form a stable carbamate. Moderately hindered amines form unstable carbamates and thus provide more free amine molecules for removal of acid gases (e.g., carbon dioxide and hydrogen sulfide). Severely hindered amines do not react with carbon dioxide to form carbamates, and can be used to remove hydrogen sulfide selectively.[1]

Creative combination of chemical and steric factors in the design of adsorbents and solvents, then, is a promising avenue toward highly selective agents.

Perhaps the ultimate examples of combined chemical and steric interactions are enzyme-based separations. Some current research is leading to chiral agents that offer intriguing possibilities for economical separation of optical isomers. In fact, companies in both Japan (Ajinomoto) and Germany (Degussa) are already using selective enzymatic transformation on an industrial scale for the separation of racemic amino acid mixtures. Other approaches, such as affinity chromatography (see Figure 3.1) are also being investigated. The opportunities for achieving selective separations by coupling chemistry with steric interactions are so rich that, by contrast, they seem to be barely exploited. Future collaboration between synthetic chemists, with their understanding of rational design and synthesis of molecules, chemical engineers, and solution

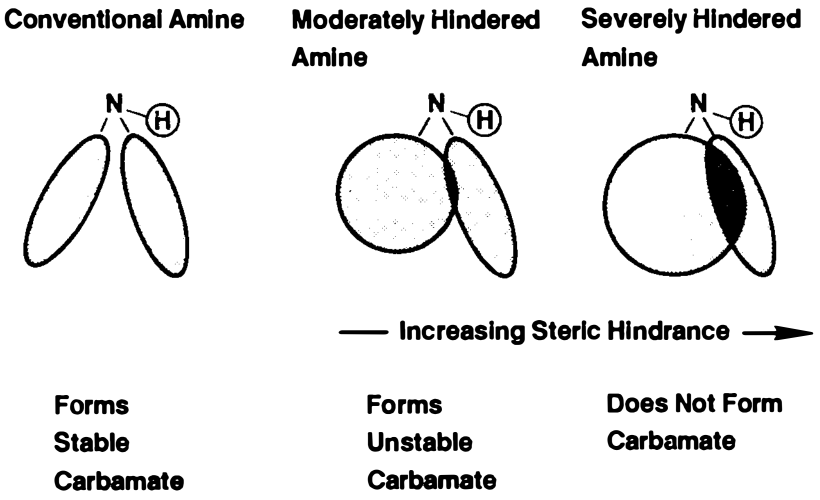


FIGURE 5.2 Using Steric Factors to Enhance the Chemical Selectivity of a Mass Separating Agent: [1] Conventional amines with linear substituent groups do not experience steric hindrance of their reactivity. Thus, they react with carbon dioxide to form stable carbamates. Regeneration of the free amine for recirculation and further reaction requires expensive equipment and considerable energy. [2] Increasing the steric bulk of the amine groups changes the reactivity of the nitrogen atom. The carbamates it forms with carbon dioxide are unstable. The task of regenerating the free amine becomes much easier, with the result that the capacity per molecule increases for the removal of carbon dioxide. The savings in energy and equipment costs, over conventional amines, can be up to 50 percent. [3] A further increase in the size of the bulky substituent group on the amine produces a molecule whose reactivity is severely hindered by the space available to the nitrogen atom. Such amines do not react with carbon dioxide, but do react with hydrogen sulfide. Thus, they provide a way to remove hydrogen sulfide selectively in the presence of carbon dioxide.

[SOURCE: Peter J. Lucchesi, Exxon Research and Engineering Company.]

chemists with their understanding of process design, molecular thermodynamics, and the statistical-mechanical and electron donor-acceptor phenomena that govern phase and complexation equilibria, will aid in the exploration of this frontier.

Physical Interactions

Other potential routes to improved selectivity rely on physical interactions to discriminate among solutes in solution. Such interactions include transport phenomena, electrical phenomena, and phenomena based on photoelectron excitation.

The phenomenon of differential transport can be used to create separations based upon rate differences. Several of the newer avenues being pursued for separation of hydrogen sulfide from gas streams rich in carbon dioxide use such approaches, as do many of the processes utilized for separation of uranium isotopes—the gas centrifuge, gaseous diffusion, and thermal diffusion. Just as steric factors can be used to enhance chemically based separations (see the preceding section on "Chemical Interactions"), the creative combination of synthetic chemistry and transport provides excellent opportunities to achieve enhanced selectivity, particularly in processes based upon surface activity and interfacial phenomena. Among these are mineral flotation and bubble fractionation.

For charged species, such as proteins and various ionic substances, electrical fields provide another useful tool for separation. Processes relying on electrophoresis separate solutes on the basis of differences in charge-to-mass ratio (actually the ratio of charge to transport resistance). Although very effective on the laboratory scale, these processes have proven vexing to scale up, because of the need to dissipate ohmic heat and to maintain streamline flow. There has recently been some indication of success with these problems, but more research is definitely warranted. The same is true of processes based on electrically driven field-flow fractionation, or electropolarization chromatography. Dielectrophoresis (the use of a nonuniform AC field to separate solutes of different polarizability or dielectric constant) is also worthy of continued investigation. So are innovative unions of electrophoresis with other means of separation, such as combinations of electrophoresis with membrane processes, or of electrophoresis with partitioning chromatography.

Finally, the development of tunable lasers has introduced the possibility of photoexciting a particular atom or molecule in a mixture in preference to the other components of the mixture. The excited state may then present the opportunity for enhanced selectivity in a separation by chemical or other means. This technique is being developed for the separation of ^{235}U from other isotopes. There are formidable barriers that may prevent the general use of lasers in separation processes, though. A molecule in its excited state is capable of becoming deactivated quickly through collisions with other molecules or through internal conversion, and may also undergo undesirable chemical reactions. Any of these pathways could result in a low yield of separated product per quantum of exciting radiation. Since energy from tunable lasers is expensive, such processes will not be economical in most cases.

Biological Phenomena

Many biological processes exhibit considerable selectivity, and the development of biologically based separations is worthy of intensive research. An example of biological selectivity in separations is the use of enzymes, monoclonal antibodies, or surface antigens as separation agents in affinity chromatography. Because biological substrates are inherently chiral, they will certainly find use in the separation of mixtures of optical isomers. Another very promising thrust, which has already met some success, is the development of cells whose walls are selectively permeable to products of biological reactions. This offers the possibility of accomplishing product fractionation through the nature of the cell wall itself.

A third use of biological selectivity is the use of microbes as biosorbents. Some microorganisms are able to preferentially absorb metals from aqueous solution with distribution coefficients greater than 10,000. Finally, the combination of advanced molecular biology with the process insights of separation scientists is also likely to lead to the design of organisms that produce only the desired isomer of a compound, thus avoiding a separation entirely. In the entire area of combining biological phenomena with separations, we have just scratched the surface of possibilities.

Membrane Processes

Membrane processes have been the subject of considerable effort by researchers seeking to achieve selective separations of solutes. Because of their importance as an avenue toward improved selectivity in separations, and because current research is integrating chemical, physical, and biological interactions, membranes and membrane processes are discussed separately in this section.

Membrane processes are based on the phenomenon of differential transport of solutes across a barrier. There are no economies of scale, equipment, or operating costs to be achieved by staging a membrane process, and with some notable exceptions (e.g., uranium gaseous diffusion) membrane processes are generally not staged. Very high separation factors are needed, then, to gain the desired degree of separation in a membrane process without staging.

This high selectivity is gained through incorporating chemical or physical interactions into the membrane. For example, by building pores of fairly uniform size into the membrane, separations based on gross differences in molecular size can be carried out. Membrane microfiltration and ultrafiltration (Figure 5.3) are based on this principle, and can give nearly infinite separation factors, or selectivities, when solutes are very different in molecular size. The ability of polymer scientists to achieve uniform pore sizes in membranes is much more limited than with molecular sieves, though, and for solutes that do not differ greatly in molecular size it is not yet possible to achieve sharp size-based fractionations.

Facilitated-transport membranes represent another way in which chemical selectivity can be built into membranes. These membranes incorporate a mobile carrier agent, which serves to react with the solute of interest on the feed side of the membrane and carry it over to the permeate (product) side. This chemical reaction can greatly increase selectivities among solutes. The properties sought for the chemical transport agent are very similar to those sought for a complexing extractant: the chemical interaction must be strong enough to give the desired selectivity, but cannot be too strong since the agent must release the solute on the product side of the membrane. These impregnated membranes (or solid-supported "liquid" membranes) increase the capacity and selectivity of separation processes without incurring the limitations of emulsion formation and feed contamination that sometimes accompany solvent extraction processes.

For membrane separations of liquid mixtures in general, gaining improved selectivities among solutes is not simply a matter of creating a better structure in the membrane. Present membrane processes for liquid feeds are complicated by the phenomena of *membrane fouling* and of *concentration polarization* in the liquid boundary layer adjacent to the membrane surface. Fouling seems to result from the preferential attachment of certain solutes or suspended matter to the membrane surface, and/or build-up within membrane pores. Concentration polarization is a build-up of rejected solutes near the membrane

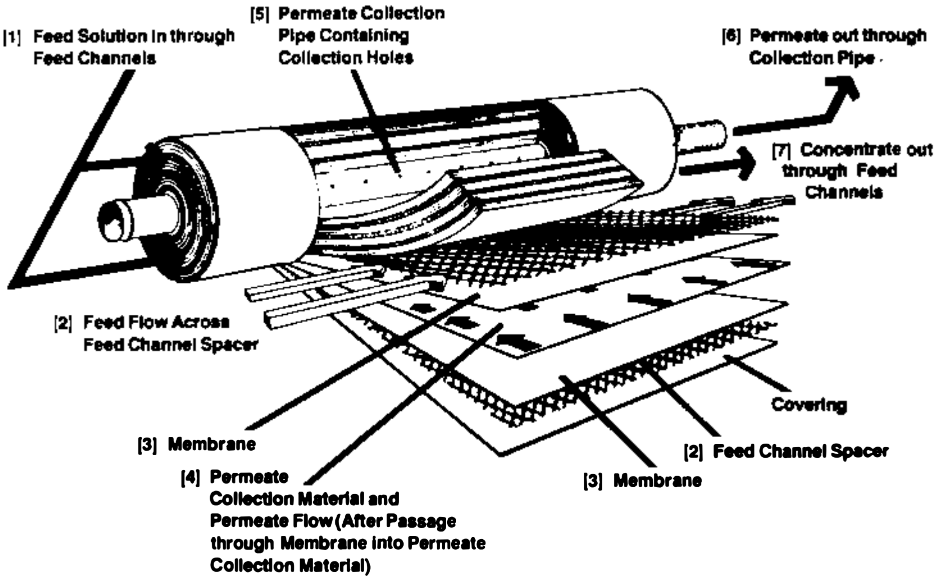


FIGURE 5.3 Ultrafiltration: Ultrafiltration membranes contain pores of fairly uniform size. These membranes can selectively separate molecules that differ grossly in size. An example of a spiral-wound ultrafiltration module is shown above. The feed solution, containing the molecule of interest, is injected under pressure [1] into a feed channel that is wound in a spiral. The feed channel contains a spacer [2] that introduces some turbulence into the flow. This helps to prevent concentration polarization and fouling at the membrane surface. On either side of the feed channel is an ultrafiltration membrane [3] that performs a size-based separation. The permeate, consisting of small molecules that fit through the membrane, flows through a collection material [4] that leads down to and then surrounds a collection pipe [5]. The pipe contains holes through which the permeate flows and is then collected [6]. The remaining material in the feed channel consists of a concentrated solution of large molecules that can also be collected [7]. Ultrafiltration membranes currently find their greatest use in the processing of food and dairy products and the recovery of electrophoretic paints.

[SOURCE: William Eykamp, Koch Membrane Systems, Inc.]

surface. This build-up is caused by limitations on the rate at which the rejected solutes can be transported back into the bulk of the solution by diffusion or other processes. Solutes of low enough diffusivity or high enough concentration can actually precipitate at the membrane surface. Selectivities of membrane processes for liquid mixtures, especially with solutes of higher molecular weight, are strongly influenced, and usually diminished, by fouling and concentration polarization. Strategies to lessen fouling tendencies and to mitigate the effects of concentration polarization are required to achieve improved selectivity with membranes. These strategies will also have the benefit of improving the size-selective properties of the membrane itself.

Avenues for research include continuing the search for nonfouling or low-fouling membrane materials. Related research in the biomaterials area may provide useful leads here. Relief of concentration polarization is a matter of dissipating energy to the boundary-layer region in a way that most effectively and economically promotes mass transport of solute. This has been a goal of research for years, and consequently there are probably few promising leads left to be uncovered. Electrophoretic depolarization methods deserve continued attention.

Membranes can also be used in combination with other separation forces or phenomena to generate improved separations. One such approach, deserving of further evaluation, is to use selective precipitation, micelle formation, complexation, or chelation with macromolecular reagents on the feed side as a means of achieving more complete rejection of a solute by an ultrafiltration membrane.

> **Summary Recommendation:** The most important generic research goal is to develop highly selective agents that can discriminate among chemically similar species in a readily reversible process. Research relevant to this goal focuses on understanding and generating separating agents with specific chemical, physical, or biological interactions at the molecular level.

RECOVERING SUBSTANCES FROM DILUTE SOLUTIONS

Many of the most important current and future separation needs involve recovery of substances from solutions where they are present at low concentrations. The problem of dilute solutions occurs throughout various methods for production of substances by biotechnology, as well as in hydrometallurgical processing of metals and minerals and in recovery of substances from effluent streams for recycling. The most common solvent, by far, in these dilute solutions is water.

The distinguishing feature of dilute solutions is that handling and processing costs for the solvent become dominant. This situation occurs for concentrations ranging from very low, up to 10 or 20 percent by weight. In some cases (e.g., expensive bioproducts, detoxification of wastes), one can be faced with the need to remove or recover a gram, or less, of material from a tank car of solution.

The committee felt that the problem of dilute solutions is sufficiently pressing, and yet sufficiently general, that it sponsored a workshop on the subject, held in Knoxville, Tennessee, in October 1985. This was attended by persons from a wide variety of backgrounds, including biological processing, hydrometallurgical processing, environmental control, and separations in general. A report stemming from this workshop is available.[2]

Classically, the first step that is carried out in such a situation is to remove large quantities of solvent selectively, so as to increase the concentration of the solute(s) of interest and to decrease the volume of material that must be subjected to further processing. The reduction in volume considerably lessens the cost of subsequent processing. However, the strategy of separating dilute solutions is itself challenging, and has recently been analyzed by Lightfoot.[3]

The most common separation process for concentrating dilute solutions by removal of solvent is evaporation. Evaporative concentration is used on a very large scale in corn wet milling, in the manufacture of sugar from sugar beets and sugar cane, and in the concentration of citrus juices, among other applications. Evaporation has been widely used for a long time. It is energy-intensive, but the energy consumption can be reduced by use of the multieffect principle. It is unlikely that many further improvements will occur, with the possible exception of the development of devices for more efficient heat transfer. The use of evaporation for products of biotechnology is frequently limited by the thermal sensitivity of the products.

Two alternative approaches for solvent removal are freeze concentration and membrane processes. Both of these offer the possibility of lower energy consumption, compared to evaporation. They also both offer promise for considerable improvement, given well-directed research.

Freeze concentration to remove water from aqueous solutions typically suffers from problems associated with the formation of very small and plate-like crystals and from the resultant difficulties in washing these crystals free from the concentrate. Problems of incomplete separation of solute from the crystallized solvent may also arise from adsorption onto crystal surfaces and occlusion or incorporation into the crystal structure, as well as from entrainment. Greater knowledge concerning mechanisms of solute distribution and/or effective avenues toward larger crystal sizes could make freeze concentration become more widely used.

Membrane processes used for concentration of dilute solutions are reverse osmosis for simple solutes and ultrafiltration for macromolecular solutes and colloidal matter. As already mentioned, two fundamental limitations to these processes are the build-up of solute-rich layers adjacent to the membrane surface and membrane fouling. In addition to causing lower selectivity between solvent and solute, these phenomena also decrease the available rate of throughput of solvent, thereby making the required membrane area larger. Improved approaches to overcoming concentration polarization, however unlikely, would be highly desirable, as would more selective, high-flux, thermally stable, nonfouling or low-fouling membranes.

An entirely different approach for concentrating dilute solutions is to "pluck" the solute of interest out of solution in a highly specific manner. One way of doing this is to use a selective mass separating agent, such as a sorbent or solvent. Recent research in Japan has resulted in very impressive adsorption routes for concentrating uranium from its very low natural concentration (about 3 parts per billion) in seawater. A process of this sort faces the challenge that the highly specific sorption or extraction process should also be reversible, so that the solute can be recovered at high concentration from the separating agent by regeneration. This is not a simple prescription. A separating agent that is able to concentrate a highly dilute substance usually binds that substance very tightly.

Another way of "plucking" ionized solutes out of solution is to use electrochemical separation methods. The energy consumption of these methods is directly related to the amount of solute recovered. Thus, energy consumption is nearly independent of the degree of dilution of the solute in the feed, except in extremely dilute solutions, where ohmic loss of electrical energy becomes important. Electrochemical separations in quite dilute solutions represent a promising line of research, on which little research has been done so far.

Electrodialysis processes are another avenue toward the recovery or removal of ionized species from aqueous solution. Here again, the solute is what is removed, with the result that the energy consumption is primarily related to the amount of solute, rather than the amount of solvent (water). This makes electrodialysis processes most suitable for ionic solutes in dilute solution.

Electrodialysis with bilayer membranes, which consist of a sandwich of an anion-exchange membrane and a cation-exchange membrane, with the apparent property of splitting water present between the layers into hydronium and hydroxyl ions, is being investigated as a method to separate ionized salts while converting them simultaneously to the corresponding free acid and base. Such a development could be useful for biological processing, where optimal reaction conditions often correspond to a level of pH (relative acidity) that results in the desired product appearing in the salt form. This electrodialysis method should receive continued attention and development to assess its potential. The same is true for any other method of separation that gives the promise of recovering salts from dilute aqueous solution while simultaneously converting them into the corresponding free acid and base.

A final approach to removing solutes selectively from dilute solutions, rather than removing solvent, is through the use of composite, charge-mosaic ion-exchangers. Processes built around these materials are being investigated in Australia (the Sirotherm Process, which uses mosaic resins for removing salts from water) and in Japan (a membrane process for selective permeation of electrolytes from aqueous solutions). The advantage of the composite resins is that regeneration can be performed by a temperature swing. Conventional ion-exchange resins for similar applications, in contrast, require the consumption of chemicals (usually strong acids and bases) for regeneration.

In sum, there is a very large potential for the development of effective separating agents for selective and specific removal of desired solutes from dilute solutions. These opportunities are probably even greater than those for developing improved solvent-removal processes for concentrating solutions. Promising directions include development of adsorbents that have low porosity but satisfactory transport rates, agents whose binding mechanism changes with changes in temperature or pH, and chemical extractants that co-extract only small amounts of water of solvation. Many of the sorts of research challenges for utilizing chemical and biological interactions to build highly selective agents, mentioned in the preceding section on "Generating Improved Selectivity Among Solutes in Separations," are applicable to the problem of creating selective agents for concentrating dilute solutions by removing the solute.

Summary Recommendation: The most promising research on better methods of concentrating dilute solutions will focus on the development of processes and agents for selectively "plucking" solutes from dilute solutions. New separating agents will be needed to discriminate between solute and solvent, much as the selective agents in the preceding section discriminate among solutes. Electrochemical, electrolytic, and charge-mosaic processes offer possibilities for selective solute removal. The most promising areas for research on concentration by solvent removal, as opposed to solute removal, are membrane processes and freeze concentration.

UNDERSTANDING AND CONTROLLING INTERFACIAL PHENOMENA

Many important steps in separation processes occur in the interfacial region between phases. Matter in its three states can form five interfaces between two phases: solid-solid, solid-liquid, solid-gas, liquid-liquid, and liquid-gas. The last four are important in separation processes, yet there are large gaps in our knowledge of phenomena that occur at them. Interfacial phenomena relate to separation science in at least two ways.

The first is that many separation processes utilize substances that are interfacially active. Examples of separation processes in which surface-active materials are utilized are flotation, selective flocculation, liquid-liquid extraction, and liquid membrane separations. All of these separation methods involve complex interfacial phenomena that are critical to the separation process.

The second effect of interfacial phenomena is that the rates of many separation processes are affected by interfacial mass transfer resistance or enhancement due to the presence of surface-active compounds, which alter the structure of the interfacial region relative to the bulk phases or alter fluid mobility. This effect is seen in separation processes based on adsorption, liquid-liquid extraction, and crystallization. Mass transfer in these processes can be significantly affected by interfacial phenomena, and the effects can be either positive or negative. For example, in solvent extraction or liquid membrane systems, strongly polar extractant molecules polarize water molecules in the interfacial region, forming an interfacial structure that can retard mass transfer. On the other hand, surface-active molecules reduce interfacial tension, resulting in breakup of drops to smaller droplets, and hence in larger total surface area for mass transfer. The presence of surface-active materials in crystallization can change the size or shape of crystals, and consequently the degree and rate of separation of crystals from liquids in a crystallizer.

Research is needed to define the structure of interfacial regions in solution and to explore more fully the influence of interfacial phenomena on mass transfer. A critical thrust should be the development of workable instrumental techniques for such studies, with capabilities comparable to those of techniques developed for the study of solid surfaces. Electrochemical methods are one of the more useful approaches to studies of solid-liquid and, more recently, liquid-liquid interfaces and the effects of fields on separations at these interfaces.

Other high-priority areas of research are the study of interfaces in three-phase systems (liquid-liquid-solid and gas-liquid-solid interfaces), understanding aspects of interfacial stability important in emulsification and demulsification, better understanding of the effects of external fields on interfacial transport, and practical research on utilizing interfacial phenomena to advantage in separations. One critical area for practical research supported by fundamental investigations is characterization and handling of process slimes. Such materials pose a severe environmental problem, and they are extremely difficult to process for disposal.

Despite the importance of interfacial phenomena to separation science and technology, not enough attention has been given to this area by researchers in either academe or industry. This is a fertile field with great potential.

> **Summary Recommendation:** There are large gaps in our knowledge of phenomena at fluid-fluid and fluid-solid interfaces that affect many separation processes. A critical thrust would be the development of instrumental techniques for studying these interfaces. Other high priorities are studies of interfaces in three-phase systems; aspects of interfacial stability important in flotation, emulsion, and foams; effects of external fields on interfacial transport; and practical research on utilizing interfacial phenomena to advantage in separations.

INCREASING THE RATE AND CAPACITY OF SEPARATION SYSTEMS

As important as energy costs are in separation processes, capital charges often exceed energy costs. As was noted in Chapter 2, separations often account for a large fraction of plant capital costs. Capital charges are directly related to equipment size and process complexity. Thus any reduction in size or complexity will result in real economic benefits to the process. Downsizing equipment can have a further cost-reduction benefit: smaller equipment sizes make modularization more practical. Building plants in modules and transporting them to the construction site can effect significant cost savings for the overall system, as well as for individual pieces of equipment.

To make equipment size and complexity reduction practical, it is necessary to increase the volumetric productivity of existing equipment. Fundamental research opportunities that will meet this goal include developing high-capacity separation reagents and improving the flow patterns in separation equipment. Probably the most important elements are increases in mass-transfer rates, since the size of equipment for most separation processes depends on them. There are several avenues for increasing these rates. These would include, for example, decreasing the length of the diffusion path, increasing the driving force, increasing interfacial area, and imposing convective forces. Basic research on hydrodynamics in separation equipment should be given more attention. The development of continuously staged contactors should receive particular attention. Attention should also be given to studying the use of external fields other than gravity in separation equipment.

As processes are scaled up, separation performance often declines because one or more of the improvements discussed above cannot be sustained. Heat-dissipation effects and the maintenance of high interfacial areas and specific flow patterns upon scale-up are two important fundamental problems for study. In processes involving mass-separating agents (e.g., adsorption, solvent extraction, and absorption), equipment can be downsized if higher-capacity agents can be developed or the turnover rate of the agent can be increased. Research aimed at high-capacity mass-separating agents should be encouraged for this reason, as well as for reasons of selectivity and concentrating power.

Advances in improving rate and capacity will require the solution of fundamental chemical, mass-transfer-rate, hydrodynamic, and process-control problems. Continuous or semicontinuous systems for adsorption separations could allow higher turnover rates by circulating or moving an adsorbent or other solid mass-separating agent between two or more zones, thus requiring solids transport. Considerable fundamental work is required to understand and predict mass-transfer rates under high-concentration, high-load conditions for which the usual linear mathematical analyses are not applicable.

Finally, it should not be forgotten that in some cases the best way to increase rate and capacity in separations is to move to processes based on entirely different concepts. For example, cryogenic systems for the separation of hydrogen from gas mixtures have been supplanted in a number of cases during the past few years by newly developed, less energy-intensive membrane systems.

> **Summary Recommendation:** Emphasis should be given to means for effecting large increases in volumetric productivity and minimization of process and equipment complexity, stressing development of continuously staged contactors, development of high-capacity sorbents and mass separating agents, studies of hydrodynamics in process equipment, and the study of the effects of external fields on flow patterns in separation equipment.

DEVELOPING IMPROVED PROCESS CONFIGURATIONS FOR SEPARATION EQUIPMENT

The number of basically different process configurations used for separations is rather small, and similar configurations are often used for separations based upon quite different phenomena. There is considerable opportunity for reducing costs and widening the applicability of various separation methods by creating novel and improved process configurations.

Making Fixed Beds Continuous

A prime example of what can be accomplished is afforded by rotating-valve and related technologies, which allow fixed-bed adsorptive separations to be carried out in a continuous mode. As is shown in Figure 5.4, feed and take-off points are moved continually along a fixed bed at discrete time intervals, making the adsorption and desorption zones move continually along the bed. This innovative approach toward making the inherently batch fixed-bed contactor continuous has resulted in a proliferation of processing plants using the technique. As of 1984 there were 60 large industrial implementations of one form of this technology, covering six different types of separations for products as diverse as para-xylene (precursor of polyesters), linear paraffins (jet fuel), and high-fructose corn syrup.[4]

A somewhat similar approach to making fixed beds more nearly continuous involves a multipipe, multivalve process, which advances the location of fixed beds along a flow sequence at discrete intervals of time. This approach has been used for years to manufacture instant coffee and is seeing expanded use for applications such as separations of fructose from glucose, as well as other separations of biologicals. Such a process has several degrees of freedom, which can be used advantageously for process improvement. Other innovations in equipment configuration should be possible to avoid solids transport, or to achieve solids transport without attrition and axial mixing. Similarly, other innovations should be possible for implementing chromatographic and adsorptive separations on a large scale. In addition to equipment configurations that enable isolating several products in a continuous operation, these can include the use of multiple force fields, multiple separation principles, and multidimensional cascades.

Internals of Contactors

Recent advances in boundary layer and dispersion theory, and in fluid mechanics, should permit more rational design of such internal components as packing and distributors. Improvements in these components should lead to

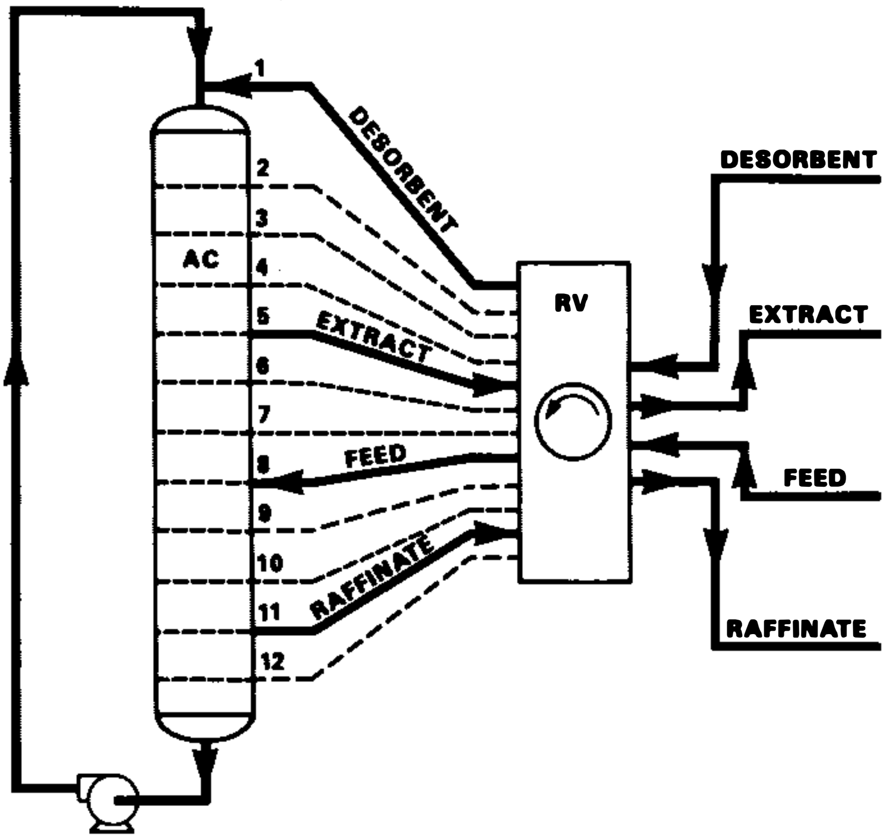


FIGURE 5.4 Making Fixed Beds Continuous—The Sorbex Process: The illustration shows an innovative approach to making a fixed-bed separator, which is inherently suitable only for batch operation, suitable for continuous operation. A rotating valve (RV) controls the flow of four liquid streams to an adsorbent chamber (AC) containing a fixed bed of adsorbent material. Incoming streams of the feed mixture and a desorbent specific to the desired product, and outgoing streams of the extract with the desired product and a raffinate containing other materials, are moved continually along the adsorbent chamber at discrete time intervals, thus making the adsorption and desorption zones move continually along the chamber.

[SOURCE: Norman N. Li, Allied-Signal Corporation.]

reduced equipment size and process stream inventories. In addition, transient response times should be shortened, simplifying start-up and improving process control. One can expect increased mass transfer effectiveness and reduction of form drag, with a consequent increase in fluid handling capacity and less flow segregation in packed columns. It should also be possible to decrease the deleterious effects of surface-tension gradients in continuous countercurrent contactors, as has been achieved in large distillation columns through operation in a spray rather than a foam regime. Such modifications should both improve the performance of existing equipment and facilitate the development of novel configurations such as the ICI "HiGee" contactor. (See "Centrifugal Distillation" and Figure 5.5 on pages 59 and 60.) Similar improvements are to be expected in solid-fluid contactors by using cylindrical packing elements instead of randomly shaped granules.

Axial Mixing

Another pervasive problem in many sorts of separation equipment is axial mixing, which reduces both the concentration-difference driving force for transport and the beneficial effects of countercurrent flow. Both these factors increase equipment size and cost, and can also lead to undesirably large flow rates and energy consumption. A promising recent approach for avoiding axial mixing in shown in Figure 5.6. Magnetic stabilization of fixed or expanded beds greatly reduces axial mixing without other deleterious effects. Nonspherical particles can be oriented preferentially in magnetic fields, offering additional avenues toward improved contactors.

Contactors that provide high ratios of flow rates of counterflowing streams are particularly susceptible to axial mixing, since the high-flow stream tends to drag the lower-flow stream backward. There is a need for contactors that avoid this problem effectively, especially for air- and water-treatment applications where it is economically important to use solvent flow rates that are much lower than the flow rate of the stream being treated.

Overcoming Capacity Limits of Separating Agents

In processes that use solvents and other mass separating agents, the uptake capacity of the separating agent for the desired solute is often an important economic limit, necessitating high solvent circulation rates. In membrane processes one can use the mass separating agent in the mode of a thin transport barrier, where the desirable separatory effect is obtained but the capacity limit of the agent is, in effect, avoided. Liquid membrane separations are another promising approach of a different sort for overcoming the same capacity limits experienced with solvents in conventional liquid-liquid extraction modes.

Other Opportunities

As has been observed earlier, mineral flotation is a process much in need of better fundamental understanding and the resultant process improvements, and these needs include the configurational aspects of flotation. Flotation devices are typically large, well-mixed vessels. It should be possible to improve their effectiveness by designing them to create axial concentration

CENTRIFUGAL DISTILLATION

Distillation is by far the most widely used separation process in the organic-chemical, petroleum, natural-gas, and allied industries. This wide use has prompted the development of very large, highly efficient columns which can have diameters up to 30 feet or more and heights up to 200 feet or more.

Distillation's energy profligacy has been extensively chronicled. Less well known is the fact that its capital costs (which derive primarily from the investment in both the column and supporting equipment and facilities) are often as great or greater than its energy costs. Realization of this fact has caused one company, Imperial Chemical Industries (ICI) in the United Kingdom, to question whether a massive, vertically oriented cylinder containing either trays or packing represents the optimal geometry for distillation. Might a more compact structure offer significant investment savings? From ICI's research has come "HiGee" technology, which radically shrinks the size of distillation equipment. Figure 5.5 shows a schematic diagram of a HiGee "column."

The factors that cause conventional distillation columns to be so large are the need to promote intense vapor-liquid phase mixing and the need to disengage the two phases after that mixing. Typically these mixing and disengaging operations occur many times in a column. The HiGee concept makes use of a high-gravitational field to increase the rate of both these operations, thereby reducing equipment size. The heart of the technology is a donut- or annular-shaped drum or rotor filled with a proprietary mesh material. This rotor spins to produce an acceleration at the mean diameter of about 1000 times the standard gravitational acceleration. Liquid is fed at the inner surface of the rotor and passes outward; vapor is fed at the outer surface and passes inward, creating the desired countercurrent-contacting zone. The result is incredibly intense and efficient phase contacting and phase separation. Volumetric-capacity reductions up to 1000-fold over standard columns performing the same separations are claimed.

This major size reduction comes with a penalty, however. That penalty is the mechanical complexity of the device. Rotating equipment costs more per unit size than stationary equipment and also has a higher maintenance cost. A motor or turbine is also required to drive the rotor. In addition, all of the other capital costs associated with a distillation column for example, those deriving from the reboiler, the condenser, the piping, the instrumentation, the control-room allocation, the analyzers, and assorted other overheads remain essentially the same, and these costs are far from negligible compared to the capital costs of the column itself. The result is that the investment-reduction picture is somewhat clouded. In addition the HiGee technology does not save on energy costs.

These facts have caused industry to go slow in accepting HiGee technology, and it appears that the initial applications will be those for which smallness is a virtue in and of itself, irrespective of the column-investment picture. An example is a distillation that must be carried out on a drilling rig in the ocean. Here space is at a premium, and a substantial investment reduction in the rig can occur by using a HiGee device. A second example is a distillation step in a modular plant—a plant constructed in one location in the form of modules and then shipped to its production site. In such a situation it might not be possible to build a large distillation column in a shippable module, and the use of a HiGee device might be the only practical way to overcome the problem. Here again the savings for the overall plant resulting from modular construction could be large irrespective of the relative investments of HiGee and conventional columns.

Having passed its initial technological testing, HiGee technology is now undergoing its initial stages of economic testing. If the early applications can show that solid economic returns can be achieved and that mechanical problems are minimal, then we can expect to see a rapid increase in the use of HiGee technology. And if this increase occurs, it will constitute the most radical substitution of one separation technology for another in this century.

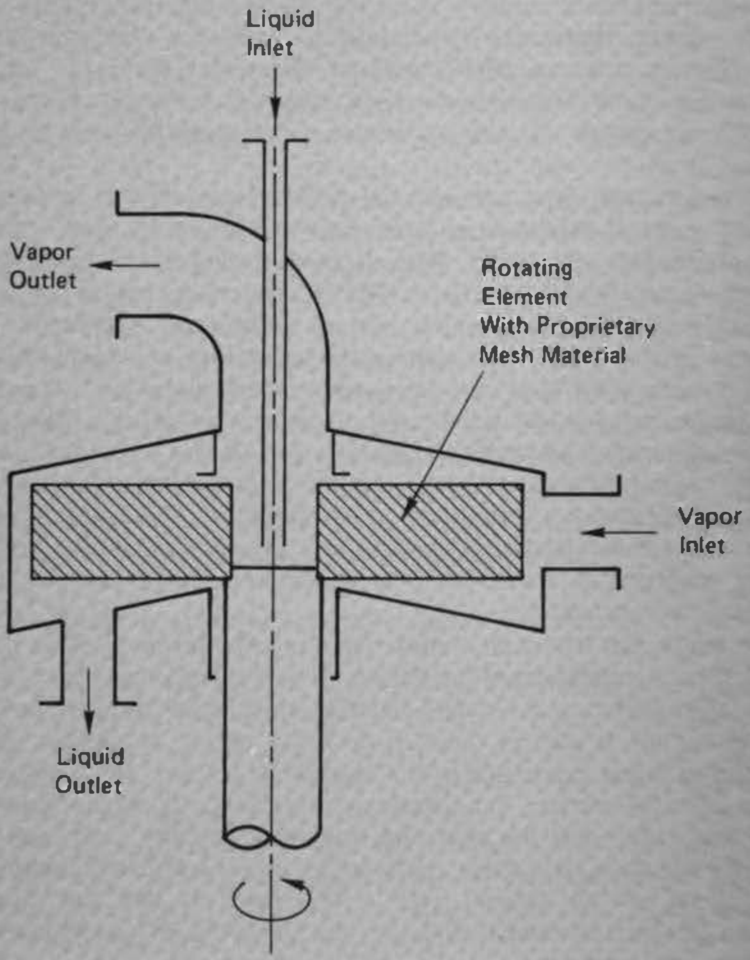


FIGURE 5.5 Diagram of the ICI HiGee Column.

[SOURCE: G.E. Keller II, Union Carbide Corporation.]

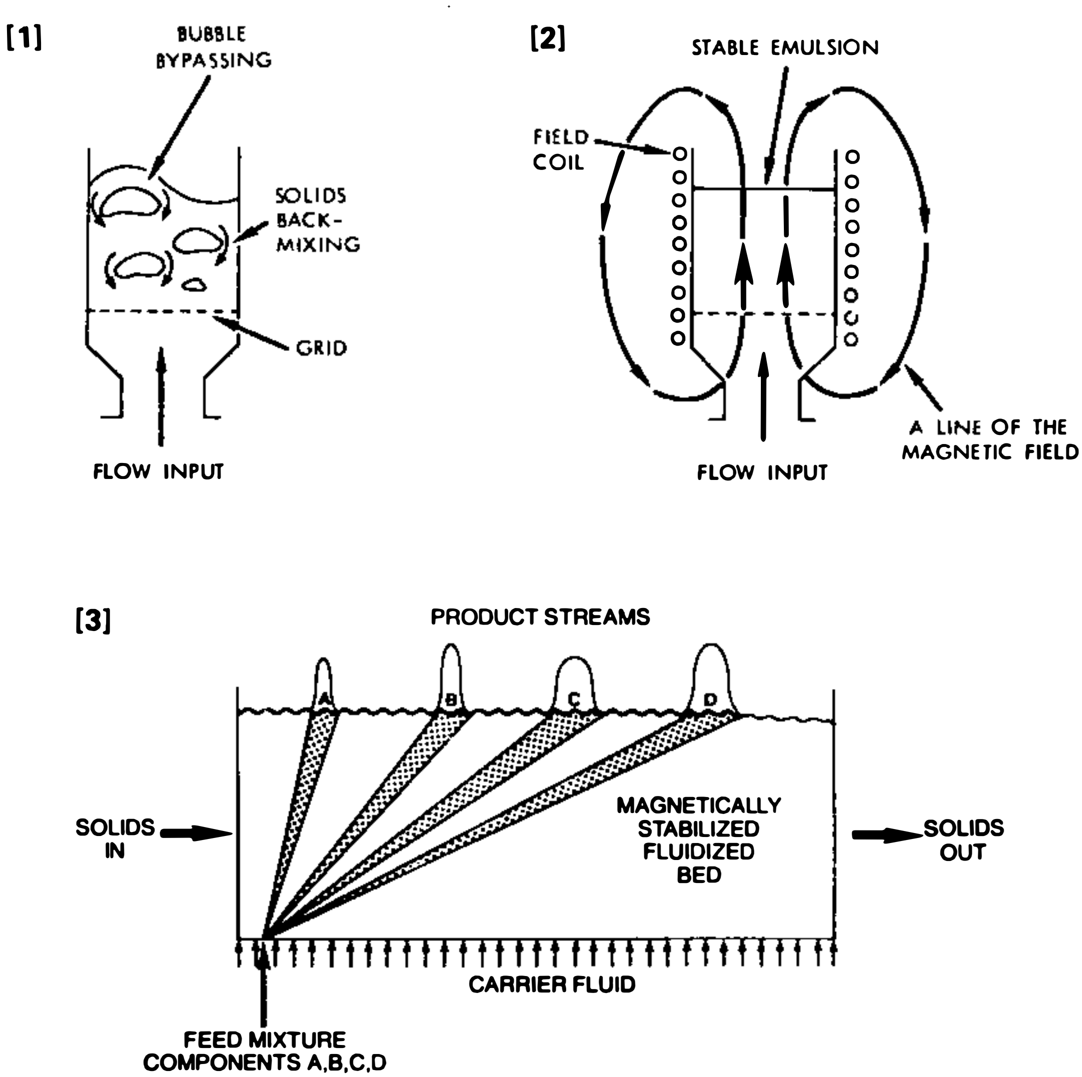


FIGURE 5.6 Magnetic Stabilization of Moving Beds: A major problem of separation schemes that rely on moving beds of solids is shown in [1]. Back-mixing of solids and bubble-bypassing impair the effectiveness of the system for achieving efficient separations. This problem can be avoided by designing a fluidized bed of particles that can be stabilized in a magnetic field [2]. A magnetically stabilized bed chromatograph [3] can then be designed, with solids flowing in a horizontal direction (as shown in the illustration) and a carrier fluid for the chromatograph introduced as the fluidization medium and flowing vertically through the bed. A multicomponent feed is injected continuously in a zone at the bottom of the bed. The components have varying adsorption/desorption characteristics with the bed solids. Weakly adsorbed components [A] will come to the surface of the bed close to the feed point, while strongly adsorbed components [C, D] are transported downstream with the solids and reach the top of the bed at different positions. Collection of the different components may be acheived by removing them at the bed surface at these different positions.

[SOURCE: *Separation Science and Technology*, 19, 1984, 977. Copyright (c) 1984 by Marcel Dekker, Inc. Used with permission.]

gradients, and possibly also by introducing the various feeds at different locations.

Flow through contacting equipment is most often carried out by using gravity as the motive force. Other types of contactors that do not rely upon gravity should be created. Such contactors would offer the possibility of reducing axial mixing, reducing equipment volumes and costs, and making economical separations that cannot be accomplished well by using gravity-driven flow.

Another promising route for innovation is the use of transient and oscillatory modes of operation. These modes can stabilize flows (as in pulsed wash columns), can allow use of much smaller amounts of separating agent (as in the new "molecular gate" adsorptive process for separation of gases), and should make possible some separations that are not feasible with steady-state operation.

Electrophoresis and other separation processes driven by electric fields have been considerably hampered by natural-convection mixing resulting from dissipation of ohmic heat. Membrane-moderated electrophoresis, or electrodecantation, is a way of coping with this problem on a moderate scale, but is limited to only two product streams. Better control of secondary flows and heat dissipation in electrophoretic separators may come from more sophisticated process modeling. Other means of dealing effectively with the heating problem are needed.

The field-flow or polarization-chromatography class of separations (Figure 5.7) has received considerable research over the last decade and now shows promise for expanding use in analytical and production-scale separations.

Yet another configurational need is for ways of integrating separation synergistically with other processing steps. As but one example, many

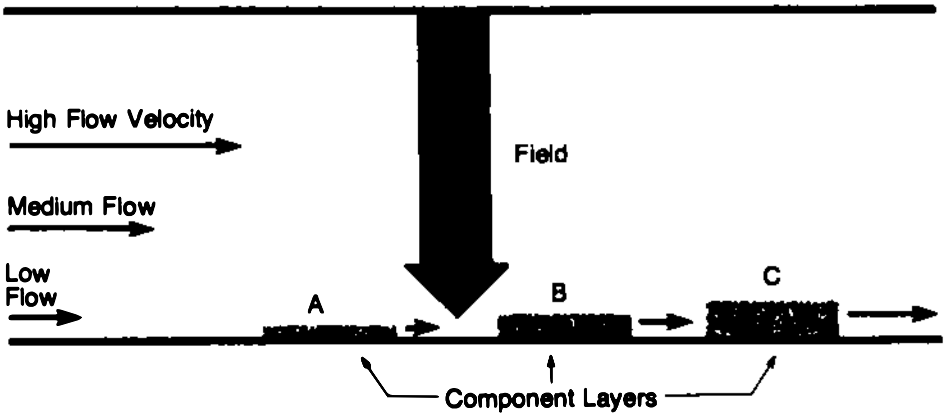


FIGURE 5.7 Using External Fields to Perform Separations: The illustration shows a cross-section of a flow channel in a separation method known as field-flow fractionation or polarization chromatography. The field or gradient applied across the thickness of the channel compresses solutes into layers of different thickness, depending on how strongly they interact with the field. The thinner the layer, the slower its progress down the channel because of frictional drag near the wall of the channel. Zones A, B, and C are, of course, diffuse at the top and the edges; this figure shows only the relative compression and its effect on downstream motion.

[SOURCE: Reprinted with permission from *Analytical Chemistry*, 53(11), 1981, 1174A. Copyright (c) 1981 by the American Chemical Society.]

fermentation reactions are product-inhibited. Accomplishing product removal directly in the fermentor can allow a higher rate of fermentation per unit fermentor volume. So far, the approaches to making this combination involve circulating large recycle flows through external extractors, membrane units, or adsorbers. More efficient synergisms should be possible, given the greater understanding that research will yield.

> **Summary Recommendation:** Improved and novel separation equipment configurations should be sought. Goals include utilizing fixed beds in continuous processes, solving the problems of axial dispersion in separation equipment, developing contactors that rely on force fields other than gravity, utilizing transient and oscillating modes in separation equipment, and integrating separation operations with other process steps for greater efficiency.

IMPROVING ENERGY EFFICIENCY IN SEPARATION SYSTEMS

In spite of recent downward trends in energy prices, these prices are still substantially higher than those of the early 1970s, and the long-term price trend will undoubtedly be upward. Since separation steps are among the largest energy consumers in many chemical processes, research aimed at reduction of energy use in separations is a critical area for investigation. Several thrusts in this area can be highlighted.

The first is heat integration or heat reuse. If the heat rejected in a distillation column condenser can be used to provide reboiler heat to a second column, the net heat requirement for the combination will clearly be reduced. Although such a scheme has been used for many years in multieffect evaporators, its use for complexes of stills and other separation processes is relatively limited. Conceptual methods for specifying optimal heat-integration arrangements are being developed, but much more needs to be done. For example, the use of side reboilers, side condensers, heat-pump cycles, sloppy cuts followed by precise cuts, and the feeding of reflux from one column to another constitute a partial list of relatively unexplored avenues for increasing heat integration. Tools for analyzing and specifying optimal process configurations for these operations are rare.

Integration of heat flows between units inevitably causes process perturbations in one unit to affect the operation of another unit. Thus research on process control and process dynamics becomes vitally important in making heat integration practical. The process-control problem is not confined to the maintenance of steady-state operation, however. Just as important is the problem of start-up and shutdown of a heat-integrated set of columns. Such operations should be carried out in such a way that a minimum of extra reboilers and condensers is required, so that investment costs can be minimized. Effective modeling techniques are critical for an understanding of process dynamics and interactions. Opportunities can be identified for heat-integrating different unit operations, such as distillation and extractive distillation, and these should also be investigated.

A second thrust is process substitution. Little research has been done to define opportunities for economically replacing a high-energy-consumption process such as distillation with a lower-energy-consumption process such as solvent extraction or adsorption. Criteria are needed to identify situations in which such substitutions could be economical and to identify which processes to substitute.

A third thrust is process combination. In separations in which nonideal phases exist, a process such as distillation may require low energy inputs over part of the composition range, while over other parts either energy requirements are high or the separation is impossible. Effecting the complete separation of ethanol and water is a classic example. Methods of combining distillation with either azeotropic or extractive distillation or adsorption have been investigated, but not in any systematic way with respect to optimal heat integration. Substantial reductions in energy use and novel process combinations can be expected to emerge from fundamental studies in this area.

A fourth thrust is low-energy methods for regeneration of mass separating agents. In processes like solvent extraction, extractive distillation, or adsorption, the principal energy consumption is nearly always for regeneration of the mass-separation agent. Methods of reducing this consumption by techniques such as staged pressure reduction, partial stripping of the agent, split-flow and multiple-recycle designs, and use of multiple effects in the regeneration step are realistic possibilities awaiting fundamental studies to provide directions.

> **Summary Recommendation:** At the systems level, continued development of heat-integration and more efficient control strategies should be pursued. Research is needed on combinations of processes to reduce energy usage for a given separation and for the regeneration of mass-separating agents.

REFERENCES

1. G. Sartori and D.W. Savage, *Ind. Eng. Chem. Fundam.*, 22, 1983, 239.

2. Proceedings of the Workshop on Challenges and Opportunities in Separation Science and Technology for Dilute Solutions, Knoxville, Tennessee, October 24-25, 1985. Washington, D.C.: National Academy Press, 1987.

3. E.N. Lightfoot, Jr., and M.C.M. Cockrem, "What Are Dilute Solutions?" in Proceedings of the Workshop on Challenges and Opportunities in Separation Science and Technology for Dilute Solutions, Knoxville, Tennessee, October 24-25, 1985. Washington, D.C.: National Academy Press, 1987.

4. D.B. Broughton, *Sep. Sci. Tech.*, 19, 1985, 723.

6

Needs of the Field

EDUCATION IN SEPARATION SCIENCE AND TECHNOLOGY

Education takes many forms. Education pertaining to separation science and technology should and will take place primarily in universities, but not exclusively so. In addition to formal coursework, important aspects of education can also occur through:

- collaborative research;
- addressing current problems in practice;
- formalized continuing education programs;
- professional journals and meetings of professional societies; and in other ways.

The universities have two important roles—codifying and communicating knowledge, and discovering new knowledge. New knowledge comes primarily through research, many of the needs for which are discussed elsewhere in this report. In this section the focus is upon codification and communication of knowledge.

The Present System

Many of the elements of separations are covered piecemeal in undergraduate courses in chemistry and chemical engineering, and even though some elements are covered in a quite sophisticated fashion, an overall integrated view of the field is lacking.

In chemistry, separation processes are usually considered in analytical chemistry courses. The emphasis, though, is heavily on chromatography and its instrumental aspects. In chemical engineering, separations are covered in a course on unit operations, or a separations course emphasizing equipment design and analysis in processes such as distillation, absorption, and extraction. There has been virtually no effort to integrate or coordinate the analytical chemistry and chemical engineering courses, one reason being that chemistry and chemical engineering are almost always separated organizationally in university systems. While separations also appear in the curricula of biochemistry, metallurgical and nuclear engineering, these are almost always addressed with little or no considerations that serve to unify separation problems or methods.

Cross-Fertilization

There is clearly a need for greater unification and design of instruction in separation science and technology, and for greatly enhanced cross-fertilization among disciplines.

An easy recommendation could be to establish disciplinary or interdisciplinary degree programs in separation science and technology. But the committee does not believe that this would be wise because of the likelihood that the resultant breadth would also engender a shallowness that would severely limit the capabilities of the graduates.

Instead, the committee strongly recommends that the educational process start with a firm grounding in one of the classical disciplines, such as chemistry, chemical engineering, or biochemistry. These provide the intellectual tools and mastery of general principles that the practitioner in separation science and technology must have in order to be effective. The aim, then, is to take persons well-versed in one or more classical disciplines and to build bridges among them that will facilitate bringing multidisciplinary approaches to separation needs.

One of the first and most important activities should be curriculum development. An interdisciplinary workshop should be convened to focus on the following needs:

- describing the elements of separations now in the curricula of chemistry, chemical engineering, and related disciplines (e.g., biochemistry, nuclear engineering, and metallurgy);
- discussing means of developing a more integrated approach to separation science and technology and how these could be incorporated in various curricula.

The workshop would be dedicated to outlining where curricula are now and where they should be, and would suggest practical means of getting from here to there.

The Classical Disciplines

Chemical Engineering. The spectrum of employment for chemical engineering graduates is changing markedly. The chemical and petroleum industries no longer dominate the picture as they did in the past, although they remain important sources of employment. A wide variety of industries are starting to employ chemical engineers in significant numbers. These include, among others, the electronics, pharmaceutical, and food-processing industries, as well as smaller firms dealing with environmental control, energy problems, instrumentation, and a variety of other applications.

As a result of this change, it is essential that the undergraduate chemical engineering curriculum contain a course dealing with generic aspects of separations. A course of this sort on separations can replace much of the traditional unit operations course and lesser portions of courses on thermodynamics and transport phenomena. Most of the classical unit operations are, in fact, separation processes (e.g., distillation, extraction, evaporation, crystallization, and drying). Distillation should be a constituent of such a course, but should receive less emphasis, since many of the areas of most current interest (e.g., biotechnology, metals, and minerals) require other kinds of separations. More of the separations based upon chemical phenomena should be brought into this course. There should be a closer integration of the transport-phenomena and equipment aspects of separations with the underlying chemical factors that enable the separation in the first place. Aspects of phase equilibrium and chemical equilibrium have traditionally been placed in courses on thermodynamics. There needs to be a more coordinated consideration of these topics in conjunction with those separation methods that build upon those concepts.

There is a need for more texts that are well suited to such courses, as well as for effective examples drawn from different applications, many of them interdisciplinary in nature.

Chemistry. Most analytical, physical, inorganic, and biochemistry courses, cover, in one way or another, phase and chemical equilibrium, surface and colloid chemistry, electrochemistry, kinetics, acid-base and donor-acceptor theories, precipitation, distillation, extraction, ion exchange, and their multistage counterparts in various types of chromatography. However, these courses do not, on the whole, satisfy the needs of an integrated understanding of the field of separations. The sort of insight into the fundamentals required for a strong presentation of separation cries out for active collaboration of chemical engineers and chemists in the development of jointly administered courses and seminars devoted to separations. These can be elective courses available to students from various backgrounds.

Freshman chemistry introduces the student to a number of concepts that can be illustrated very effectively in the context of separations. These include ionization constants, pH effects, solubilities and solubility constants, and vapor pressure. Couching these concepts in the form of realistic and meaningful separation problems can be an effective way of both providing students with stimulating "real life" problems and introducing them to separations.

Biological Sciences. With the advent of molecular biology, separations have become one of the most important tools of the biological scientist. Isolation and purification of biochemical molecular constituents has made it possible to elucidate biological processes on a fundamental basis. Also, production of useful primary and secondary metabolites or other valuable biological fractions for biomedical applications or for commodity chemicals generally requires a significant concentration and purification process.

Until recent years, there was little interest in developing separation concepts for specific use in the biological area. In most cases, techniques developed for use in the physical sciences or process industries were simply adapted. More recently, the biological scientists and practitioners have developed innovative approaches specifically for bioseparations. Some of these are useful in solving other separation problems.

Formal coursework in separation science is usually not available in biological schools or departments. Rather, the student in the biological sciences is frequently exposed to such concepts in practical laboratory courses or courses on instrumental methods. Specific courses in bioseparations would be appropriate, especially if the students were introduced to the fundamental concepts as well as the practical applications. In this respect, an emphasis on those separation methods especially important to the biological sciences (e.g., chromatography, centrifugation, and electrophoresis) should be encouraged. Joint courses with analytical chemists and chemical engineers should be considered.

Other Disciplines. Curricula in extractive metallurgy and nuclear engineering contain instruction in those separation methods that have found particular use in the processing of ores, metals, nuclear feedstocks, isotopic mixtures, and fission products. Because of the complexity of these mixtures, many important past advances in separations have been made in these areas. In university instruction, though, the emphasis has understandably been on specific applications, without much generalization to the basic concepts of separation. Interdisciplinary courses and courses within chemical engineering and chemistry that stress generic aspects of separations should be particularly useful for spurring further innovations in these areas of application.

Cross-Disciplinary Activities

Cross-disciplinary activities in separation science and technology should be encouraged and facilitated. These activities should build upon the training in classical disciplines outlined above.

Interdisciplinary research itself provides an effective avenue toward cross-fertilization of ideas and concepts, and for providing a person trained in one discipline with some of the essential concepts of other disciplines. Important steps that could be taken to promote such activities include the following:

- government programs which explicitly encourage cross-disciplinary research in separation science and technology, and
- establishment and promotion of technical meetings and journals devoted to generic and interdisciplinary aspects of separation science and technology.

The present organization of federal government research support does little to encourage such interdisciplinary interaction. For example, within the National Science Foundation the Division of Chemistry and the Division of Chemical, Biochemical, and Thermal Engineering are budgeted separately, and there is little incentive for one division to fund research in the discipline of the other division, or for the two divisions to jointly fund a single project. We therefore urge a special initiative between these divisions that would target support to interdisciplinary research groups in separations having major and joint involvements of a chemist and a chemical engineer, a biochemist and a chemical engineer, and the like. Such an initiative could target profitably up to 25 percent of its funds to curriculum development. This initiative is described in more detail later in this chapter (see page 74).

Universities should institute more cross-disciplinary elective courses relating to separations. These would not be intended to take the place of the core courses in the classical disciplines, discussed above. In such courses, separations should again be addressed in generic fashion. These courses could very effectively bring multidisciplinary talents to bear on many of the generic needs and problems outlined in Chapter 5. Examples, a few from among many, include the design of improved sorbents and membranes, fractionation of proteins on a production scale, and solvent-extraction chemistry (including methods of regeneration). Another opportunity for such courses is to address questions of concern to society, such as the implications of purity constraints and how they should be devised and "How clean is clean?" for effluents.

Expanding upon the suggestion made earlier, the interdisciplinary workshop convened on approaches to teaching separations could provide the basis for a national committee, which would also be interdisciplinary. This committee would recommend and develop curricular outlines and materials for unified, interdisciplinary courses at the advanced undergraduate and graduate levels, and define topics, examples, and back-up material for use in existing courses in chemistry, chemical engineering, and other disciplines.

Scope of These Activities

Needs for and problems in separation science and technology are pervasive, with the result that the need for trained manpower is great. Teaching of separations in universities should be virtually universal at the undergraduate level.

At the graduate level, the committee considers it a desirable goal to have strong programs of research in separations at about half of the chemical engineering departments and half of the chemistry departments in universities nationwide. This is a considerable increase from the present level of activity. This implies also that support of separation research must be broadly distributed, rather than being concentrated into a few centers.

Continuing Education

Continuing education can be both formal and informal. In addition to actual courses, collaborative research and attendance at meetings of professional societies afford effective continuing education. Continuing education programs provide a good opportunity for persons with degrees in one discipline to learn concepts from another discipline. A joint ACS/AIChE Conference on Separation Science and Technology, proposed later in this report, would afford an opportunity for cross-disciplinary continuing education. Workshops on focused, practical problems at this conference or under the sponsorship of other bodies can generate concepts and ideas that set the stage for fundamental research.

> **Summary Recommendations:** University education in separation science and technology should continue to be firmly grounded upon degree programs in the classical disciplines, notably chemical engineering, chemistry, and the biological sciences. Within each of these disciplines the appropriate focus of separations should be on generic aspects.
>
> Within chemical engineering, a generic course on separations should replace the mass-transfer-operations portion of classical courses on unit operations, as well as smaller portions of existing courses on thermodynamics and transport phenomena.
>
> Cross-disciplinary perspectives can be developed through elective interdisciplinary courses and seminars that build upon education in the classical disciplines while dealing with generic aspects of separation science and technology. A national committee, following up on an interdisciplinary planning workshop, can provide definition for such courses, as well as for integration of separation concepts into existing courses. Graduate degrees in one discipline, following an undergraduate degree in a different discipline, afford another effective avenue to encouraging cross-disciplinary perspectives.
>
> The committee urges a joint initiative between the NSF Division of Chemistry and the NSF Division of Chemical, Biological, and Thermal Engineering to support cross-disciplinary research and education in

separation science and technology. Details of this proposal are given in the section on federal agency programs (see page 74).

The committee supports the goal of having strong programs of teaching and research in separation science and technology at about half of the university departments nationwide, in both chemistry and chemical engineering. Federal support of research in this area must therefore be distributed broadly, rather than being concentrated at a few institutions.

Continuing education affords a way to bring recent advances in separation science and technology into practice and to promote well-rounded skills and interdisciplinary research.

EVALUATED DATA AND PREDICTIVE MODELS

Obviously the design, scale-up, and even the selection of industrial separation processes require data on physicochemical properties of the systems involved. The necessary data may involve either phase equilibria, such as solubilities, or transport properties, such as diffusivities. Data can be evaluated experimentally or predicted; often predictive models are used to extend the range of available data. While much useful design information on separation processes can be developed from such data, equipment that simulates on a small scale a commercial separation process often can provide data that are very valuable for scaling up to larger process equipment. What is necessary to improve the effectiveness of these diverse approaches to design of separation processes will be discussed briefly.

There is a great deal of phase equilibrium data on many inorganic and some organic systems. However, even in a common system such as sodium carbonate-sodium bicarbonate-water, there are significant gaps in the existing data, which need to be filled. Our predictive capability for equilibrium properties of liquid-liquid and liquid-solid systems is not as good as for vapor-liquid systems, so experimental evaluation will be necessary in many of these cases.

In many simple organic systems the available data can be verified and extrapolated by the use of predictive models. Such models have been very successful in estimating vapor-liquid equilibrium (VLE) data, often for systems under conditions that would make experimental determination difficult. Accurate estimates also can be made of gas-phase diffusivities under ordinary conditions. In these and similar instances the need is for extending an already considerable predictive capability to other and more complex systems, and to more extreme conditions.

Improving the accessibility of available data certainly is desirable. Data bases that can be accessed by personal computers would probably be the way to accomplish this goal. Chemical Abstracts Service may be in the best position to determine whether implementation of such a data service would be practical.

The need in some cases is not for more data or better models per se, but rather for a more fundamental understanding of what is occurring. For example, thermal diffusivity data are ordinarily measured relative to those for toluene, but the measured absolute values for toluene keep changing. Distillation tray efficiencies decrease drastically when applied to impurities present at part-per-million levels, a phenomenon that is well known but not well understood. Although gas-phase diffusivities can be predicted accurately, diffusion of gases in microporous inorganic or polymeric systems does not follow Fick's Law and cannot be predicted well. Finally, in the case of biochemical and biological systems, we need to understand the behavior of proteins better before we can even tell what data are really necessary.

Experimental measurements made in small equipment that simulates the performance of larger equipment have proven to be valuable for the scale-up of separation processes. Two examples are the Oldershaw column for distillation and the small single-plate test filter for filtration. Refined over many years, such test equipment has proved convenient and reliable for predicting the performance of process equipment that is larger by orders of magnitude. Development of comparable test equipment for other separation processes is really needed and deserves a high priority. An example is in high-pressure liquid chromatography, where estimation of the parameters for scale-up is a problem.

Some of the many successful applications of predictive models in separation processes have been mentioned already. VLE data, gas-phase and, less accurately, liquid-phase diffusivities, and solubilities of nonelectrolytes are examples where reliable estimates of parameters can be made. Refinement of existing methods for predicting some separation parameters deserves emphasis because they can be a highly efficient use of separation research funds. An accurate and reliable predictive model can obviate the need for costly, extensive experimental measurement of those properties that are critical in separation processes. General models of separation processes are useful for scaling up from the laboratory or pilot plant to commercial equipment. Such models also permit more reliable design of control systems for separation processes, which are often a critical factor in the performance of separation steps in a plant.

It is apparent that the needs regarding separations data are complex, and supplying them efficiently will require more than a "measure more and predict better" approach. More detailed analyses of the most important needs in each area will be necessary, followed by a listing by priority of the best approaches to filling those needs. The National Bureau of Standards historically has served as a source of precise, reliable, and consistent thermochemical and other data. The NBS would, therefore, be an appropriate agency to perform the analyses of needs and listing by priority of approaches outlined above. Major grants and contracts and lead agency work by other national laboratories are other routes.

> **Summary Recommendation:** Separation research, development, and design are often hampered by a lack of reliable physicochemical data. Acquiring, evaluating, and disseminating these data should be given higher priority by the federal agencies that are concerned with separation research. The National Bureau of Standards is a logical focal point for coordinating the collection, evaluation, and dissemination of physicochemical data on separations.

PROFESSIONAL SOCIETIES AND JOURNALS

The fragmentation of components of separation science and technology among classical disciplines has led, in turn, to a fragmentation of pertinent professional societies and journals.

For example, sessions on separations are a component of the national programming of the American Institute of Chemical Engineers (AIChE). These activities deal with individual separation processes and applications, and do not emphasize either the generic aspects of separations or its ties with chemistry. Within the American Chemical Society (ACS) there is a Subdivision of Separations Science and Technology in the Division of Industrial and Engineering Chemistry. This is still a small activity that has relatively little participation from chemical engineers. Within the Division of Analytical Chemistry of ACS there is a substantial amount of programming on chromatography, but it is not tied much with other implementations of separation phenomena. The American Institute of Mining, Metallurgical and Petroleum Engineers regularly programs in areas related to separations, but with a nearly exclusive focus on particular applications.

There are also various international meetings relating to specific types of separations and meetings devoted to specific applications. Example include the International Solvent Extraction Conferences, various Engineering Foundation Conferences, and the Conferences on Separation Science and Technology for Energy Applications sponsored by the Department of Energy and the Oak Ridge National Laboratory.

Finally, there is the Gordon Research Conference on Separation and Purification, which has been held annually for over 30 years. This conference has very successfully addressed current research across the entire field of separations, and has brought chemists and chemical engineers together effectively, as well as researchers from other disciplines. The conference includes no more than about 20 presentations, by virtue of its nature, and is of necessity limited to no more than about 130 participants. It, therefore, provides only a limited coverage of the field, to a limited audience.

Thus, there are few meetings that cover both chemical and engineering aspects of separations in general. Because of the strong need for generic research in separations and because of the inherently interdisciplinary dimensions of this activity, there is a need for a much larger interdisciplinary forum that covers separations in general. The committee does not believe that this can be effectively achieved within any one of the existing professional societies. Instead, the best format would be a Conference on Separation Science and Technology, jointly sponsored by the American Chemical Society and the American Institute of Chemical Engineers. This would be patterned after the very successful National Heat Transfer Conferences, sponsored by the AIChE and the American Society for Mechanical Engineers (ASME). The committee believes so strongly in the need for an integrated forum for communicating results of separations research that it would endorse the formation of a separate professional society, modeled after the Combustion Institute, if cooperation between the ACS and AIChE were not forthcoming on a joint conference.

Separation research is also fragmented among journals, appearing in the few journals specific to separations, in the general chemical engineering literature, the analytical chemistry and chromatography literature, in some of the biological sciences literature, and in journals specific to particular separation methods. There is no lack of places to publish, but more focus on fewer media of publication would be highly desirable. Some pertinent journals are listed in Appendix A along with texts and reference books.

> **Summary Recommendation:** To stimulate more effective interchange of ideas, particularly between chemists and chemical engineers, the committee urges the initiation of a Conference on Separation Science

> and Technology that would be a joint undertaking of both the American Institute of Chemical Engineers and the American Chemical Society. Such an undertaking would require a significant commitment by both professional societies, comparable to the cooperation between the AIChE and the ASME in organizing the National Heat Transfer Conferences. Failing the establishment of such a joint conference, a new professional society should be formed along the lines of the Combustion Institute.

FEDERAL SUPPORT OF SEPARATION RESEARCH

The support of research in separation science and technology is divided among a number of different agencies within the federal government. While there is strength in maintaining a diverse funding base, there are problems as well. With few exceptions, federal support of separations occurs within the context of mission-specific programs that emphasize particular applications, rather than generic research.

In such an environment, cross-cutting research opportunities can be missed. One cogent example is the generic need for research on methods for recovering constituents selectively from often dilute, usually aqueous streams. This broad area accounts for the two highest priority research needs identified in Chapter 5, and is vitally important to three of the problem areas outlined in Chapter 4—selective recovery of products from biosynthetic and pharmaceutical fermentation processes, processing of leachates from low-grade mineral resources, and recycling of materials recovered from wastewater streams. There are no focused government programs of research addressing selectivity in separations or dilute-solution separations as a class, despite the clear need for fundamental research that would serve many different applications. Such research arguably would have the highest potential for innovations.

If the United States is to make effective and efficient progress on the key technological challenges outlined in Chapter 4, challenges that are crucial to our national well-being (e.g., a cleaner environment) as well as to our economic competitiveness in world markets (e.g., commercializing biotechnology), then a major change is needed in the way that investigators conceive and define research topics and in the ways that federal agencies plan and organize the support of separation research. The committee believes that its priority list of generic research needs (Chapter 5) provides the basis for rethinking the way in which separation research is carried out and supported. To recast the field and make progress on the most important research areas, though, will require a much larger "balanced portfolio" of federal funding. Such increased funding will enable federal agencies to stimulate work on generic research frontiers and to recruit additional talent from the classical disciplines into separations research.

As background to the following section, Appendix B contains a description and analysis of existing federal programs in separations.

Expanding and Strengthening Existing Generic Programs

The nucleus of a national initiative for separation research can be found in two existing federal programs. They are the Separation Processes Program

(SPP) within the Division of Chemical, Biochemical, and Thermal Engineering (CBTE) of the National Science Foundation (NSF), and the Program on Separations and Analysis within the Office of Energy Research of the Department of Energy (DOE). At present, both programs are too small to undertake the lead roles in the national effort that this committee envisions. The committee believes that the research frontiers in separations are sufficiently promising that the NSF program can be sustained at more than twice its present size without sacrificing quality. Similarly, nonisotope separation research at DOE should be funded at least one-and-a-half times the present level of support. A multiyear pattern of budgetary growth to achieve these program levels is vital if the nation is to benefit from the promising research opportunities outlined in this report. In both cases, the increased programs should emphasize generic research and take steps to attract additional investigators into this field.

The importance of separations and the intellectual promise of its generic research frontiers are such that it might be asked whether the NSF Separation Processes Program ought to be moved to the Division of Fundamental Research for Emerging and Critical Engineering Systems in the Engineering Directorate. The committee has considered this possibility in its deliberations. Although SPP fits several of the criteria for this Division well, the committee recommends that the expanded Separation Processes Program be retained in its entirety within the Division of Chemical, Biochemical, and Thermal Engineering. The reason for this recommendation is that the recommended increase is for generic and relatively fundamental research, which can tie closely with other CBTE activities in transport processes, chemical thermodynamics, and multiphase and interfacial phenomena.

Both the NSF and the DOE programs exist in larger organizations that fund basic research in chemistry as well as chemical engineering. These broader programs should stimulate more cross-disciplinary activity between the two disciplines in separations. The NSF Division of Chemistry and the NSF Division of Chemical, Biological, and Thermal Engineering can have a major impact on the field of separation research by jointly supporting medium-sized cross-disciplinary research collaborations in separations. The committee recommends an initiative that would target support to about 10 interdisciplinary research groups, at a level capable of supporting two to three co-principal investigators—whose backgrounds would cut across disciplinary boundaries—and about five graduate students or postdoctoral scholars per group. This initiative can also target profitably up to 25 percent of its funds for curriculum development in separations, to the extent that high-quality proposals materialize in response to a solicitation.

Even in a time of constrained budgets, this committee believes that sustained program growth in the NSF Separations Processes Program and the DOE Separations and Analysis Program, and the new joint program initiative proposed for NSF, represent wise investments in high-leverage research opportunities.

Support by NIH for Fundamental Research in Bioseparations

The National Institutes of Health (NIH) have an important stake in addressing many of the more fundamental generic research priorities outlined in this report. Better separations are needed to isolate increasingly complex bioactive substances, and incorporating biological activity into separation processes promises to result in major advances. How can NIH and the research community best address the promising opportunities in the area of fundamental bioseparations research?

Within NIH, the National Institute of General Medical Sciences (NIGMS) is probably the most appropriate "home" for bioseparations research with a generic and fundamental focus. The committee strongly recommends that the funding for NIGMS be increased to allow it to explore research opportunities in bioseparations without detriment to its existing program of research support in other areas. A new thrust in bioseparations ought to be large enough to attract high-quality proposals and to allow for a realistic examination of its accomplishments over a period of years. A funding level sufficient to enable 15 to 20 new starts annually, at an average level of $150,000 per grant, is needed to allow this new thrust to be successful.

The separation research community is relatively unfamiliar with the structure and processes of NIH. If a bioseparations program is to attract high-quality proposals, the research community and NIH will need to work together to educate potential applicants about NIH and to promote communication on the contributions that separation research can make to NIH's health-related missions. Giving a specific program officer responsibility for this endeavor is probably in order. This committee stands ready to assist in this process by organizing workshops at professional meetings on these topics, and by serving as a resource to NIH, if needed, in identifying appropriate reviewers for proposals and/or members for a special study section.

This recommended new activity for NIGMS in fundamental aspects of bioseparations research should not imply less support for, or an alternative to, the programs of more applied, but still generic, research in bioprocessing separations (e.g., DOE-ECUT) described later in this section.

A Critical Role for the National Bureau of Standards

The special need for evaluated data and predictive models for separations has already been noted in this chapter. This committee believes that the existing program in separations at the National Bureau of Standards is a logical focal point for coordinating the collection, evaluation, and dissemination of physicochemical data on separations, as well as for development of needed methods of measurement in complex separation systems, such as multiphase dispersions. In order to allow NBS to begin to play an important role in this area, an increase of about 10 percent in the resources available to the Center for Chemical Engineering can profitably be targeted towards separation research over the next few years. This will approximately double the present level of activity in the area of separations.

"Applied" Federal Programs in Separations

Department of Energy. In addition to its Separations and Analysis Program in the Office of Basic Energy Sciences, the Department of Energy supports research on separations within two programs under the Assistant Secretary for Conservation and Renewable Energy and an additional program in the Office of Energy Research.

One of these three programs, in the Office of Industrial Programs, funds research on industrial innovations in separations that could lead to substantial energy savings. Much of this work has been directed toward specific methods and specific applications. In recent years, this program has moved towards supporting research of a more generic nature. The committee supports this change in emphasis, and sees an opportunity for this program to assume a valuable role in facilitating technology transfer between the performers of basic research funded by NSF, NIH, and the DOE Office of Energy Research, on the one hand, and potential industry users of technologies based on this basic research, on the other hand. One way of doing this would be for OIP to organize a series of workshops that would bring together users and basic researchers to discuss the potential applicability of advances in separations research. These workshops might well identify areas where OIP should fund generic applied research to further develop new concepts and processes for separations that have advanced beyond the stage appropriate for sponsorship by basic research agencies, but are not yet at the stage where industry will carry forward. These two new activities should logically be supported through an increased budget.

The committee also encourages further development of the generic separations aspects of the research program on bioprocessing and biocatalysis that exists within the program on Energy Conversion and Utilization Technologies (ECUT) of the Office of Energy Utilization. The development of methods for production of organic chemicals, solvents, pharmaceutical products, and liquid fuels from biomass resources involves separations that are dominated by energy requirements resulting from the dilute-solution problem and from needs to fractionate among chemically similar substances. This recommendation is supportive of a recommendation made recently by another committee of the National Research Council, the Committee on Bioprocessing for the Energy-Efficient Production of Chemicals, chaired by Dr. George T. Tsao. Their report[1] has recommended $10 million of additional support for bioprocessing activities in the ECUT program. One of the principal areas of bioprocessing recommended for emphasis in the "Tsao Report" is separations.

It would also be most appropriate for this same office to create a separate program on generic aspects of energy-intensive separations.

The third applied DOE separation program, in the Office of Health and Environmental Research (OHER), supports research on separations associated with instrumental and monitoring techniques relating directly to environmental and health needs. Although we see the primary expansion of research on health-related areas occurring within the National Institutes of Health, the OHER program occupies an important niche. It should be augmented to support three or four additional research groups in separations. If a typical research group includes two graduate students and a postdoctoral researcher, the average grant size would be about $150,000 per year.

Bureau of Mines. Within the Department of the Interior, the Bureau of Mines funds a substantial amount of research on hydrometallurgical separation processes. This research is carried out in in-house laboratories. The current depressed state of the U.S. minerals industry, typified by diminished research efforts within industrial laboratories and, in some cases, wholesale termination of research operations, has resulted in bleak prospects for the employment of new researchers in this area. At the same time, the U.S. cannot afford to lose a professional generation of research personnel in an area that would be of critical importance if foreign supplies of certain metals were interrupted. The committee recommends that the Bureau fund a modest number of university-based Centers of Excellence in Separation Research related to minerals and metals. The research in these centers should explicitly focus on generic themes, to stimulate fresh ideas and insights in metals-related separations, to allow for technology transfer of separation concepts among research groups in academe, to facilitate exchange of ideas with researchers in other areas of separations, and to train a new generation of research scientists and engineers flexible enough either to move into a revitalized minerals industry or to find employment in the broader sector of process industries.

Environmental Protection Agency. A focus on generic separations research would help a number of other federal agencies achieve their missions more effectively. Within the realm of environmental protection, there are numerous critical separation problems. These include separations of dioxins from soils and decontamination of toxic-waste sites. Given the central importance of separations to environmental control and improvement, it would be appropriate for the EPA Office of Exploratory Research to develop a focused attention to separations; this currently does not exist. Separations in the processing of dilute solutions and analytical separations would be two obvious components of an enhanced generic program at EPA.

Department of Agriculture. There are opportunities for generic research in separations relevant to the mission of the Department of Agriculture, both in the regional laboratories and in the small program of peer-reviewed, external grants. Substantial research on separations for food processing existed at one time in USDA; it has virtually disappeared with the shift in emphasis away from post-harvest technology.

Department of Defense. Finally, the amount of basic research on separations sponsored by the Department of Defense is far less than corresponds to the potential contribution of this research to national defense interests. This contribution could result in better methods for sequestering and treating hazardous materials, manufacturing processes to produce more stable pharmaceuticals for use in the field, improved food concentration and dehydration, and enhanced production of large, defect-free crystals of ultrapure materials for new electronic technologies.

INDUSTRIAL SUPPORT OF SEPARATION RESEARCH

There is, and should be, a substantial amount of funding of research and development in various industries, pertaining to separations as well as some industrial funding of university research on separations. Of necessity, these projects are highly application-specific and often have proprietary elements. Industrial research efforts should continue and be facilitated, but they cannot be expected to shoulder a significant portion of the more fundamental, generic research efforts that are the principal recommendation of this report. Support of generic research must fall to the federal government.

While industrial funding cannot assume a major burden of support for generic research in separations, it is still important to facilitate joint university-industry efforts, through government funding and other enabling activities. Industrial consortia can be valuable, and should be encouraged. The Industry-University Cooperative Research Program of the National Science Foundation has played a valuable role, with separations being among the many areas that have received partial support.

DISCUSSION

Although they address research needs and opportunities from the focused viewpoint of generic research in separations, the recommended budget increases in the previous section are consistent with, and supportive of, recommendations that have been made in other recent reports from committees of the National Research Council.

The Committee to Survey Opportunities in Chemistry has identified fields of opportunity, national needs, and intellectual challenges spread across the field of chemistry. The report from this committee, *Opportunities in Chemistry*,[2] has noted the importance of separations for recovery and processing of strategic metals and nuclear fuels, as well as for separation of fission products (pp. 224-246), for fractionation and preconcentration in analytical chemistry (p. 252; pp. 271-276), for isolation of bioactive molecules (pp. 120-121), and for clean-up of wastewaters and ground water (pp. 206-208). At several points in this report (e.g., pp. 84-86) the importance of gaining selectivity in organic synthesis is underscored. The same avenues of chemoselectivity and stereoselectivity underlie the development of selective separating agents, one of our principal recommendations. The difference is that, for selective separation, reversibility–and therefore weak bond strength–are also important considerations.

Among the intellectual challenges noted in *Opportunities in Chemistry* are understanding solution chemistry on the most fundamental level, so as to enable advances in those methods of separation that receive or involve liquid solutions (pp. 258-259), and understanding the chemical nature of adsorption and co-adsorption at solid surfaces (pp. 243-245), which is an important avenue toward improved adsorption processes for separations.

Opportunities in Chemistry recommends that the budgets for basic chemical research at the National Science Foundation and the Department of Energy be increased by factors of 2 and 2.5, respectively, over the next few years. The recommendations of the Committee on Separation Science and Technology for separation research funding are fully consistent with these recommendations.

Separation processes and reaction engineering are usually recognized as the main areas that distinguish chemical engineering from other forms of engineering. As such, they have long been recognized as central core components of chemical engineering. The Committee on Chemical Engineering Frontiers: Research Needs and Opportunities (under the Board on Chemical Sciences and Technology, National Research Council) is currently surveying the broad field of chemical engineering. Although no report has yet been issued, one can be confident that a number of critical needs and opportunities relating to separations will be identified.

CONCLUSION

The importance and pervasiveness of separations throughout the U.S. economy indicate that a federal program of generic research, structured along the priorities recommended by this committee, could have significant benefits to our economic competitiveness. Although the nation is faced with a budgetary crisis of considerable magnitude, its need to address separation problems, both to meet pressing national needs and to maintain international competitiveness in high-technology markets, is too great to postpone the exploitation of opportunities afforded by separation research to the indefinite future. A timely response is required if these opportunities are not to slip from our grasp.

REFERENCES

1. Bioprocessing for the Energy-Efficient Production of Chemicals. Washington, D.C.: National Academy Press, 1986.

2. Opportunities in Chemistry. Washington, D.C.: National Academy Press, 1985.

Appendixes

Appendix A

General References to the Literature of Separations

BOOKS ON SEPARATIONS IN GENERAL

E.W. Berg, Physical and Chemical Methods of Separation. New York: McGraw-Hill, 1963.

E.J. Henley and J.D. Seader, Equilibrium Stage Operations in Chemical Engineering. New York: John Wiley and Sons, 1981.

B.L. Karger, L.R. Snyder, and C. Horvath, An Introduction to Separation Science. New York: John Wiley and Sons, 1973.

C.J. King, Separation Processes, 2nd ed. New York: McGraw-Hill, 1980.

N.N. Li, Ed., Recent Developments in Separation Science, multiple volumes. New York: CRC Press, 1972 and subsequent.

J.M. Miller, Separation Methods in Chemical Analysis. New York: John Wiley and Sons, 1975.

J. Minczewski, et al., Separation and Preconcentration Methods in Inorganic Trace Analysis. New York: John Wiley and Sons, 1982.

R.W. Rousseau, Handbook of Separation Process Technology. New York: Wiley-Interscience, 1986.

P.A. Schweitzer, Handbook of Separation Techniques for Chemical Engineers. New York: McGraw-Hill, 1979.

A. Weissberger and E.S. Perry, Eds., Techniques of Chemistry: Separation and Purification. (Techniques of Chemistry Series, Vol. 12.) New York: John Wiley and Sons, 1978.

F.J. Wolf, Separation Methods in Organic Chemistry and Biochemistry. New York: Academic Press, 1969.

R.S. Young, Separation Procedures in Inorganic Analysis. Bucks, England: Charles Griffin and Company, Ltd., 1980. New York: Wiley-Halsted, 1980.

BOOKS ON SPECIFIC SEPARATION TECHNIQUES

G. Astarita, D.W. Savage, and A. Bisio, Gas Treating with Chemical Solvents. New York: Wiley-Interscience, 1983.

J.C. Giddings, E. Grushka, J. Cazes, and P.R. Brown, Eds., Advances in Chromatography, multiple volumes. New York: Marcel Dekker, 1965 and subsequent.

C. Hanson, T.C. Lo, and M.H.I. Baird, Eds., Solvent Extraction Handbook. New York: John Wiley and Sons, 1983.

F. Helfferich, Ion Exchange. New York: McGraw-Hill, 1962.

C.D. Holland, Fundamentals of Multicomponent Distillation. New York: McGraw-Hill, 1981.

A. Kohl and F.C. Riesenfeld, Gas Purification, 4th ed. Houston: Gulf Publishing, 1985.

R. Lemlich, Adsorptive Bubble Separation Techniques. Orlando: Academic Press, 1972.

J.A. Marinsky and Y. Marcus, Eds., Ion Exchange and Solvent Extraction, multiple volumes. New York: Marcel Dekker, 1966 and subsequent.

A.S. Mujumdar, Ed., Advances in Drying, multiple volumes. New York: Hemisphere Publishing, 1980 and subsequent.

Proceedings of the International Solvent Extraction Conferences (ISEC). *Proceedings were published for ISEC '77, ISEC '80, and ISEC '83 under the following titles:*

Proceedings of the International Solvent Extraction Conference (ISEC '77). CIM Special Volume 21. (Two volumes) Montreal: Canadian Institute of Mining and Metallurgy, 1977.

Proceedings of the International Solvent Extraction Conference—1980. Liege, Belgium: Universite de l'Etat de Liege, 1980.

International Solvent Extraction Conference, Denver, Colorado, August 26 to September 2, 1983. Proceedings. (Selected papers) AIChE Symposium Series No. 238. New York: American Institute of Chemical Engineers, 1983.

Proceedings of ISEC '86 will be published by the Deutsche Gesellschaft fur chemisches Apparatewesen e.V. (DECHEMA), Frankfurt, F.R.G.

G.M. Ritcey and A.W. Ashbrook, Solvent Extraction: Principles and Applications to Process Metallurgy, Parts I and II. New York: Elsevier, 1983, 1984.

D.M. Ruthven, Principles of Adsorption and Adsorption Processes. New York: John Wiley and Sons, 1984.

CLOSELY RELATED BOOKS

M. Benedict, T.H. Pigford, and H.W. Levi, Nuclear Chemical Engineering, 3rd ed. New York: McGraw-Hill, 1981.

R.B. Bird, W.E. Stewart, and E.N. Lightfoot, Jr., Transport Phenomena. New York: John Wiley and Sons, 1960.

Kirk-Othmer Encyclopedia of Chemical Technology, 3rd ed. New York: Wiley-Interscience, 1978-1984.

A.L. Lydersen, Mass Transfer in Engineering Practice, New York: John Wiley and Sons, 1984.

R.H. Perry and D. Green, Eds., Perry's Chemical Engineers' Handbook, 6th ed. New York: McGraw-Hill, 1984.

T.K. Sherwood, R.L. Pigford, and C.R. Wilke, Mass Transfer. New York: McGraw-Hill, 1975.

JOURNALS ON SEPARATIONS IN GENERAL

Journal of Separation Process Technology. London: Childwall University Press.

Separation and Purification Methods. New York: Marcel Dekker Journals.

Separation Science and Technology. New York: Marcel Dekker Journals.

JOURNALS ON SPECIFIC SEPARATION TECHNIQUES

Adsorption and Ion Exchange (AIChE Symposium Series). New York: American Institute of Chemical Engineers.

Drying Technology. New York: Marcel Dekker Journals.

Journal of Chromatographic Science. Niles, Ill.: Preston Publications, Inc.

Journal of Chromatography. Amsterdam: Elsevier Scientific Publishing Co.

Membrane Science and Desalination (incorporating *Journal of Membrane Science*). Amsterdam: Elsevier Scientific Publishing Co.

Solvent Extraction and Ion Exchange. New York: Marcel Dekker Journals.

RELATED JOURNALS

AIChE Journal. New York: American Institute of Chemical Engineers.

Analytica Chimica Acta. Amsterdam: Elsevier Scientific Publishing Co.

Analytical Biochemistry. Orlando: Academic Press.

Analytical Chemistry. Washington, D.C.: American Chemical Society.

Biotechnology Progress. New York: American Institute of Chemical Engineers.

Carbon. Elmsford, N.Y.: Pergamon Press.

Chemical Engineering Journal. Lausanne: Elsevier Sequoia S.A.

Chemical Engineering Science. Elmsford, N.Y.: Pergamon Press.

Environmental Science and Technology. Washington, D.C.: American Chemical Society.

Hydrocarbon Processing. Houston: Gulf Publishing Co.

Hydrometallurgy. Amsterdam: Elsevier Scientific Publishing Co.

Industrial and Engineering Chemistry Research. Washington, D.C.: American Chemical Society.

Polyhedron (incorporating *Journal of Inorganic and Nuclear Chemistry*). Elmsford, N.Y.: Pergamon Press.

Reactive Polymers, Ion Exchangers, Sorbents. Amsterdam: Elsevier Scientific Publishing Co.

Talanta. Elmsford, N.Y.: Pergamon Press.

Appendix B

Federal Programs Supporting Separation Research

Separation science and technology is a broad, multidisciplinary area of vital importance to major national and societal needs. It is not surprising, then, that research in this field is supported by a number of federal agencies and programs.

The purpose of this appendix is to describe the general scope and interests of the current federal programs supporting separation research, both to provide detailed background for the comments made in Chapter 6 regarding these programs, and to provide the researcher interested in exploiting the research opportunities described in this report with a guide to programs where funding may be found.

Of course, the comments in this section are constrained by the general uncertainty regarding federal budgets for research in a time of budgetary stress. The descriptions that follow attempt to portray these federal programs as they existed in fiscal year 1985.

NATIONAL SCIENCE FOUNDATION

The focus for fundamental separation research within the National Science Foundation is the Separation Processes Program (SPP) in the Division of Chemical, Biochemical, and Thermal Engineering. This program was created in 1982, and has a consistent history of budgetary growth. In FY 85, the program stood at $3.15 million and funded about 25 percent of the proposals received. Some examples of research areas supported by the program include membrane technology, adsorption, ion exchange, chromatography, extraction, distillation, and various novel separations. As part of the recent reorganization of the NSF Engineering Directorate, some topics in minerals processing, such as flotation, came under the aegis of SPP in FY 85. This reorganization also resulted in the establishment of a Division of Critical and Emerging Systems, containing a program on biotechnology. This program was funded for FY 85 at nearly $2.0 million, and included some activities related to separations.

Within the NSF Division of Chemistry, the Chemical Analysis Program funds separation research related primarily to chromatography. Its effort in this area approached $1.8 million in FY 85, approximately 16 percent of the program's budget.

DEPARTMENT OF ENERGY

There is substantial support for separation research in many of the mission areas of the Department of Energy including the large applied programs that are responsible for fossil energy, solar energy, and nuclear energy. More fundamental and generic research in separations is also supported by at least four administrative units. Two of these are in the Office of Energy Research and are administered by the Division of Chemical Sciences within the Office of Basic Energy Sciences and by the Division of Physical and Technological Research within the Office of Health and Environmental Research. The other two are under the Assistant Secretary for Conservation and Renewable Energy, in the Office of Industrial Programs and the Office of Energy Utilization Research.

Office of Basic Energy Sciences

The Separation and Analysis Program within the Division of Chemical Sciences of the Office of Basic Energy Sciences had a budget in FY 85 of approximately $12 million. Of this amount, separation research, including isotope separation projects, totalled approximately $7 million. Isotope separation projects accounted for $1.3 million. One notable aspect of this program is the large fraction of support going to projects at the National Laboratories and other large contractors (for example, Mound Laboratories of Monsanto Research Corporation). These account for over $4.5 million of the $7 million total. The overall budget for this program is fairly stable, and about 20 percent of proposals received are funded.

The basic themes of this program mirror the concerns of DOE, including chemical analysis, isolation, and preparation of stable and radioactive isotopes, hydrometallurgical processes and techniques (especially related to the nuclear fuel cycle), and separations of hydrocarbons. The separations program at academic institutions (about 25 research groups are supported) also includes a number of investigations of novel separation concepts.

Office of Health and Environmental Research

The Division of Physical and Technological Research under the Office of Health and Environmental Research supports the mission of that office with research in a variety of applied areas. This includes separation research, especially that associated with instrumental methods and monitoring techniques. There has also been support for the development of separation technology for the recovery and purification of biological research materials.

Office of Industrial Programs

Another major DOE separation program is located in the Office of Industrial Programs under the Assistant Secretary for Conservation and Renewable Energy. This program funds research on innovations in industrial separations that could lead to substantial energy savings; its budget was between $1.0 and 1.5 million in FY 85 and has been fairly stable in the past few years. It is estimated that 30 to 40 percent of the projects funded by the program are carried out in universities. Research areas supported included indirect freeze concentration emphasizing applications in the food and paper industries, membrane research focused on petrochemical, food, and brine applications, and chemical and physical analyses of liquors from the manufacture of pulp and paper.

This work is of a different character than that supported by the DOE Office of Energy Research, stressing innovations in specific processing methods that might lead to patents and be taken over directly by industry, if the research is successful. It is probable that some projects of high risk but of potential high energy savings would not be started in industry without impetus from this DOE program.

Office of Energy Utilization Research

This office, also under the Assistant Secretary for Conservation and Renewable Energy, is about five years old. Within it is a biocatalysis program, funded for FY 85 at the level of $2.5-3.0 million per year. The program emphasizes research on the selectivity of biological catalysts (e.g., enzymes) and on separation methods for bioproducts, notably those commodity chemicals for which energy costs for separation would be a substantial fraction of product value. These activities address research needs and opportunities for bioprocessing, including generating improved selectivity and processing of dilute solutions.

BUREAU OF MINES

The Bureau of Mines of the Department of the Interior carries out research directed at the specific processing needs of the minerals industry. Separation research is funded primarily by the Extractive Metallurgy Technology Division and the Materials and Recycling Technology Division in the Minerals and Materials Research Program. This research is almost entirely in-house at six research centers: Albany Research Center, Oregon; Avondale Research Center, Maryland; Reno Research Center, Nevada; Rolla Research Center, Missouri; Salt Lake City Research Center, Utah; and Tuscaloosa Research Center, Alabama. Both generic research and commodity-specific research are conducted, with the goal of improving existing metallurgical processes. A significant amount of research in hydrometallugical processes is supported.

The size and scope of separation research at the Bureau of Mines has been declining over the past few years. Extramural grants to research groups in universities are no longer made, and the Extractive Metallurgy Technology Division received a 25 percent cut in its FY 86 budget, from $17.5 million to $13.5 million. The Mineral Institutes Program, which supported interactions between the BOM and universities in a number of areas, including comminution, is being phased out in FY 86. The FY 85 funding level for this program was $9 million.

NATIONAL BUREAU OF STANDARDS

The National Bureau of Standards (NBS) established a Center for Chemical Engineering at its laboratories in Boulder, Colorado, and Gaithersburg, Maryland, in 1981. Within the Division of Chemical Engineering Sciences of the Center, NBS has begun an in-house program on separation processes. The new separation activity in NBS is a small program (a budget of approximately $1 million and 8 FTE professional staff in FY 85) and focuses primarily on facilitated-transport membranes and emulsion liquid membranes. It is branching into measurement and property-determination needs for bioseparations of proteins and similar complex molecules.

NATIONAL INSTITUTES OF HEALTH

The National Institutes of Health (NIH) fund a number of projects related to basic separation research in the National Institute of General Medical Sciences. This Institute has recently taken greater interest in supporting research related to process engineering for biotechnology. While there appears to be only a small amount of NIH research directed towards separations now, this amount will probably increase in the future.

DEPARTMENT OF AGRICULTURE

The extramural research activities supported by the USDA are carried out by three mechanisms: the Cooperative State Research Services, a program of Special Competitive Grants, and a Competitive Grants Program. It is difficult to determine if any separation research is supported by these programs. The USDA also sponsors a considerable amount of research through the Agricultural Research Service (ARS). Almost all of this research is conducted in-house, though the ARS funds some research at universities under cooperative agreements with USDA laboratories. Within ARS, some separation research is carried out at the Eastern Regional Laboratory in Philadelphia. Overall, with the redirection of USDA research efforts in the past several years toward pre-harvest technology and energy problems associated with agriculture, the activity of USDA in food processing research and relevant separations has become much less.

PRIVATE SOURCES OF SUPPORT FOR SEPARATION RESEARCH

While this appendix has focused on federal sponsorship of separation research, it should be noted that the Gas Research Institute and the Electric Power Research Institute also support research in this area. Within EPRI, support for separation research is spread over several programs, with about $350,000 of support from the EPRI's Industrial Programs office over the last 3 years. Most of this research is in processes and applications development including applications of heat pump technology to separations, a major effort in freeze concentration, membrane research, and electrolytic separations.

CONCLUSION

A summary table for federally sponsored separation research is shown below. Two characteristics of these data stand out—the relatively small size of the U.S. effort in separation research, compared to the importance of separations for U.S. industrial competitiveness, and the small percentage of existing funds going to study the fundamental science of separation processes. Aside from the small NSF programs and the program in the DOE Office of Basic Energy Sciences, most separation research programs focus on specific applications, rather than on understanding generic phenomena. This point is discussed in more detail in the section on "Federal Support of Research in Separation Science and Technology" in Chapter 6.

TABLE B.1 Summary of Federal Support for Separation Research

Agency or Program	FY 1985 Budget (thousands of dollars)
National Science Foundation	
Separation Processes Program	$ 3,150
Chemical Analysis Program	1,800
Department of Energy	
Office of Basic Energy Sciences	7,000
Office of Industrial Programs	1,250
National Bureau of Standards	1,000
Bureau of Mines	13,500
TOTAL	$27,700

Appendix C

The Contribution of Separations to the War Effort: 1940-1945

The last great national "push" for better separation technologies came during World War II, as America and her allies were challenged to apply new knowledge from the frontiers of physics, chemistry, and biology to the war effort. This search for better separations was not viewed at the time in those terms, but separations quickly proved to be the key problems in wartime crash programs to manufacture commodities as diverse as synthetic rubber, blood plasma, uranium, and penicillin. The following examples suggest that had a more coherent body of knowledge about separations existed before the war, these projects would have been significantly speeded towards their conclusion.

STYRENE–KEY INGREDIENT FOR SYNTHETIC RUBBER

In the early 1940s, the Japanese war machine swept through the western rim of the Pacific Basin, and sources of natural rubber on which the United States had depended to a large degree were lost. It quickly became obvious that development of alternative sources of rubber would be an essential feature of preparation for war. Synthetic rubber was given a high priority, and plans were formulated to begin producing styrene-butadiene rubber.

At this time, styrene was produced as only a specialty chemical. The most obvious synthetic route to styrene, by the catalytic dehydrogenation of ethylbenzene, faced formidable problems in adaptation to large-scale production. To begin with, the reaction that occurred as ethylbenzene was passed over a catalyst resulted in less than 50 percent conversion of ethylbenzene to styrene. The resulting mixture of compounds included the desired styrene, unreacted ethylbenzene, and side products such as toluene and benzene. The straightforward way to separate such a mixture of organic chemicals, distillation, could not be used since styrene would polymerize at temperatures well below its boiling point under normal atmospheric pressure, resulting in fouling and plugging of the distillation equipment. It was recognized that styrene could be made to distill at lower temperatures by conducting the process under a partial vacuum, but there was considerable doubt that a distillation column could be designed that would both function under a partial vacuum and separate styrene from ethylbenzene, a compound whose boiling point is almost the same as that of styrene.

As a result of the lack of a satisfactory distillation technology, a costly but foolproof alternative process was built (Figure C.1). Ethylbenzene was first oxidized to acetophenone. Acetophenone was then hydrogenated to form (1-hydroxyethyl)benzene. Finally, (1-hydroxyethyl)benzene was dehydrated to styrene. Distillation of styrene from ethylbenzene was completely avoided, but at a tremendous penalty in terms of energy costs, investment in process equipment for this multistep process, and raw material efficiency.

The crash program for synthetic rubber stimulated efforts at Monsanto, Dow, and elsewhere to improve vacuum distillation. The only practical design possible, given the then current state of the art in distillation column internals, was to split the fractionation between two columns in series, with complete recondensing and reboiling of the vapors between the two columns. This primary-secondary column system consumed a great deal of energy in heating and cooling utilities, but was preferable to the multistep chemical reaction route to styrene.

The dual-column configuration for styrene distillation remained in use until 1964, when Union Carbide's Linde Division commercialized new high-capacity, low-pressure-drop trays for use in distillation columns for this separation. These internals allowed single-column distillation to be carried out, at a 25 percent energy savings for the overall process and a considerable savings in equipment and associated costs. Since that time, breakthroughs in research on structured packings for distillation columns have led to even more efficient columns for this process.

The styrene story clearly shows the importance and far-reaching impact of generic research into better equipment configurations, including the design of the internals of separation equipment such as distillation columns. The Linde trays that revolutionized styrene manufacture in 1964 were the product of years of research on cryogenic separations of liquid air into oxygen and nitrogen. Their application to styrene is an illustration of a generic idea crossing the boundary between applications. Had more been known about the efficient design of column internals prior to World War II, inefficient and cumbersome routes to styrene would not have been needed to provide America with synthetic rubber, and wartime rationing of tires and other rubber articles might not even have been needed.

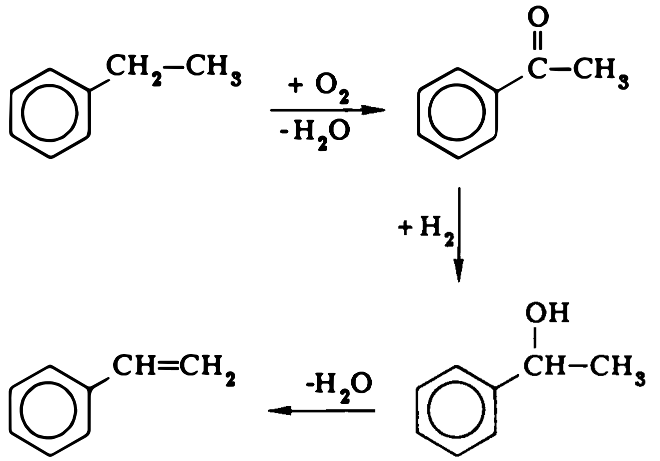


FIGURE C.1 Synthesis of Styrene from Ethylbenzene.

[SOURCE: G.E. Keller II, Union Carbide Corporation.]

PENICILLIN

As German bombs fell on England in 1940, a group of researchers at Oxford University was carrying out the definitive experiments that established penicillin's ability to act as an antimicrobial agent in the treatment of systemic infections. They found that penicillin was even effective against organisms, such as staphylococcus, for which there were no effective drugs. The penicillin preparations used in these experiments were highly dilute (less than 1 percent penicillin), impure (contaminated, for example, with fever-producing impurities), and unstable (penicillin stored in solution could become inactivated under a wide variety of conditions). Because of wartime conditions in England, the Oxford researchers looked to colleagues in the United States for assistance in bringing penicillin into large-scale production for medical use.

The problems to be overcome in accomplishing large-scale production were numerous and formidable. Important contributions to their solution were made during the war by chemists, chemical engineers, biochemists, and biologists of all stripes. Yet the problems of purifying and stabilizing penicillin proved to be key challenges in bringing about penicillin production on a commercial scale. This was made possible by separation research.

The crude broths from *Penecillium* cultures at that time contained only 20 to 60 parts per million (ppm) of active penicillin. These crude broths also contained dissolved solids at 1,000 times the level of penicillin, and included many compounds whose chemical properties were similar to those of penicillin. Up to 1943, when researchers knowledgeable in separations first became involved in the penicillin production effort, industrial manufacturers employed a batch purification process consisting of adsorption of penicillin on activated charcoal followed by elution with chloroform and processing of the chloroform solution of penicillin. About one-third of the potentially recoverable penicillin was actually recovered by this process; the majority of penicillin originally produced was lost by decomposition or deactivation during recovery.

When chemical engineers at Shell Development Company were first brought into the penicillin recovery problem, they were able immediately to put to use existing generic knowledge of two-phase extraction with pH gradients to design a continuous countercurrent extraction process. The process was complex and somewhat cumbersome, involving five different extraction steps, but it worked. Within three months, the new process was established and demonstrated. Within seven months of their initial involvement, an integrated pilot plant using this process had been constructed and was processing 200 gallons of fermentation broth per day. Recovery of penicillin in the pilot plant was nearly 85 percent, with less than 5 percent being lost to deactivation in the recovery process. Four penicillin producers installed the Shell process, and it played an important role in boosting penicillin production nationwide from a rate in the second half of 1943 capable of sustaining the treatment of 4,100 patients per month to a rate in the second half of 1944 equivalent to treatments for nearly 250,000 patients per month.

As successful as the Shell process was, it still suffered from a number of problems. An important difficulty arose whenever penicillin broths were placed in contact with water and organic solvents, and were stirred. Emulsions--complex and stable mixtures of broth components, water, and the organic solvent formed and persisted, trapping the penicillin in the interfacial region made up by the emulsion and preventing extraction of the penicillin into or out of the organic solvent. A second problem was the impracticality of concentrating penicillin in one pass through the process, from the crude broth to the optimum level needed for final processing. The Shell process required a flash evaporation of water at a pressure of 5 torr (atmospheric pressure is about 760 torr) to provide a concentrated liquor suitable for final processing.

The problems called for extractor equipment capable of using high centrifugal force to break up emulsions, combined with process improvements to reduce the number of extractions and boost the final concentration of the penicillin solution emerging from the process. These advances were largely achieved late in the war by the introduction of the centrifugal multistage solvent extractor by Walter J. Podbielniak and his co-workers (an example of a Podbielniak contactor for vapor-liquid separations is shown in Figure C.2). The three-step extraction using the "Podbielniak contactor" boosted penicillin recovery to nearly 95 percent. A major difficulty in implementing the process was the need to filter solids from the crude broths prior to the first centrifugal contacting step. Emulsions that formed were exceedingly difficult to handle, and the total lack of any theory of emulsification or demulsification, or even an understanding of the basic interfacial phenomena involved, forced process engineers to proceed on a time-consuming trial-and-error basis.

After the difficulties of separating penicillin from its fermentation broth were largely solved, a final challenge remained. Penicillin, in solution, was easily rendered inactive by a wide variety of conditions. A stable form of penicillin was needed for storage and shipment to hospitals and clinics. This could be accomplished if penicillin could be separated, without deactivation, from the aqueous solution in which it emerged from the process. Crystallization was tried without success. Flash evaporation under high vacuum was costly

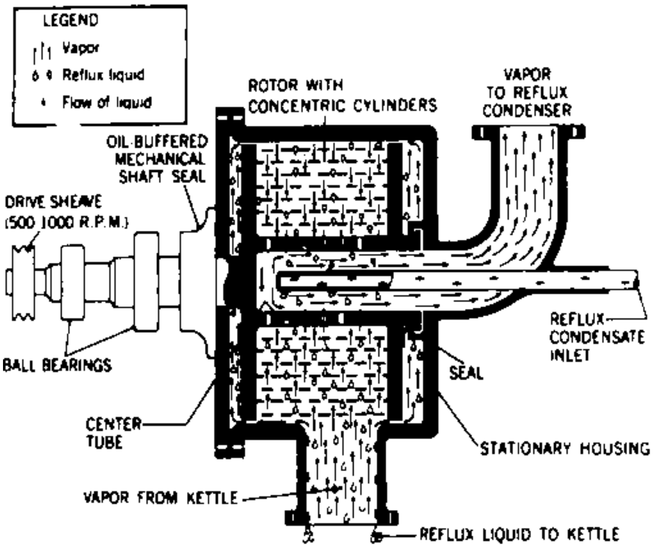


FIGURE C.2 Centrifugal Multistep Solvent Extractor ("Podbielniak Contactor"). This diagram illustrates the principle of the Podbielniak Contactor for a vapor-liquid separation.

[SOURCE: W.J. Podbielniak, H.R. Kaiser, G.J. Ziegenhorn, *Chem. Eng. Prog. Symp. Series*, 100 (1970), 46. Copyright (c) 1970 by the American Institute of Chemical Engineers and used with permission.]

and inefficient. Researchers then turned to freeze drying, in which the aqueous solution containing penicillin was first frozen to ice, followed by removal of water by direct sublimation from ice to water vapor under vacuum. Freeze drying had never been implemented on a production scale before this time. The large-scale use of vacuum techniques and the complex limitations on rates of heat and mass transfer involved in freeze drying were unknown. Progress came only after a crash project led by Thomas K. Sherwood at M.I.T. during 1942-1943 established enough understanding of the fundamental phenomena involved to enable the construction of workable production plants.

In the postwar years, the problem of crystallizing penicillin from aqueous solution was finally solved, obviating the need for freeze drying. The knowledge of freeze drying obtained from the World War II penicillin project formed the basis for later industrial use of freeze drying of foods, beverages, and pharmaceuticals.

Production of penicillin would have been achieved more rapidly, with much less cost, if there had been better understanding of interfacial phenomena in liquids, if there had been more generic knowledge of centrifugal contactors, if the inherent rate limitations in freeze drying had been better understood, and if there had been better communication across disciplinary lines among scientists (e.g., chemists, biochemists, and biologists) and chemical engineers specializing in separations.

URANIUM

Perhaps the best-known technological undertaking of World War II was the Manhattan Project, which resulted in the first use of the atomic bomb. While much attention has been given to the accomplishments of theoretical and nuclear physicists in designing the bomb, less attention has been focused on the role that was played by chemists and chemical engineers who produced the needed uranium and plutonium for the bombs that ended the war.

As found in nature, uranium consists principally of two isotopes--uranium-235 and uranium-238--that have similar chemical properties but different masses and radioactive characteristics. Uranium-235 alone is useful for maintaining nuclear fission, but it is present in only very low concentration (0.7 percent) in naturally occurring uranium. Moreover, the chemical similarities between uranium-235 and uranium-238 make their separation from one another very difficult by standard methods. A variety of separation processes were tried during the Manhattan Project to enrich the isotopic composition of uranium to the needed level of greater than 90 percent uranium-235.

The first samples of uranium-235 obtained were isolated in mass spectrographs by A.O. Nier and E.O. Lawrence. By the end of 1941, the latter was able to report that he could deposit in one hour one microgram of uranium-235 from which a large proportion of the uranium-238 had been removed. The principle underlying this electromagnetic separation of uranium isotopes is shown in Figure C.3. A sample of uranium is ionized, and when the charged ions of uranium traverse a magnetic field, their paths bend into arcs or curves whose radii are proportional to the mass of the ion. The dominant design of electromagnetic separators used during the Manhattan Project was built on this principle and called *calutrons* because the prototype used the magnet of the University of California Cyclotron.

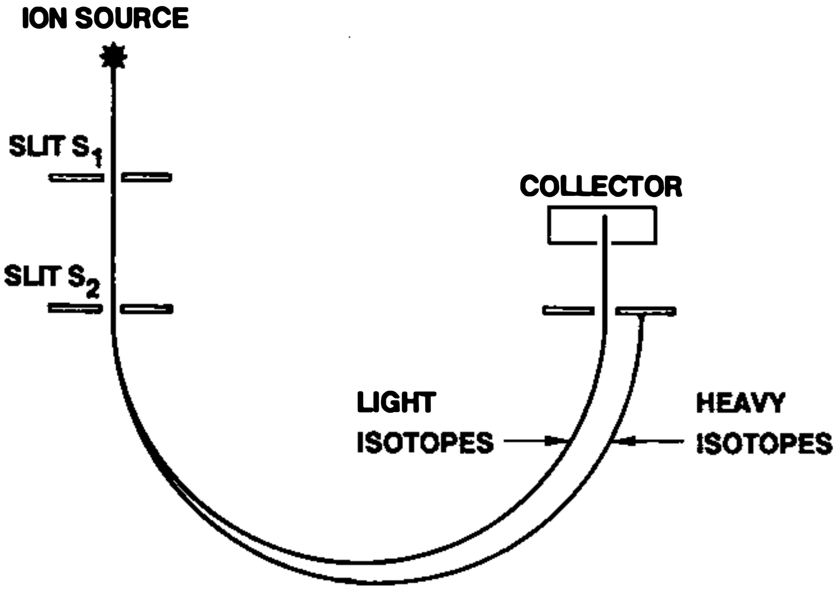


FIGURE C.3 Mechanism of Electromagnetic Separation of Isotopes. When charged ions traverse a magnetic field (in the illustration the field is perpendicular to the page), their paths bend into circles whose radii are proportional to the mass of the ions.

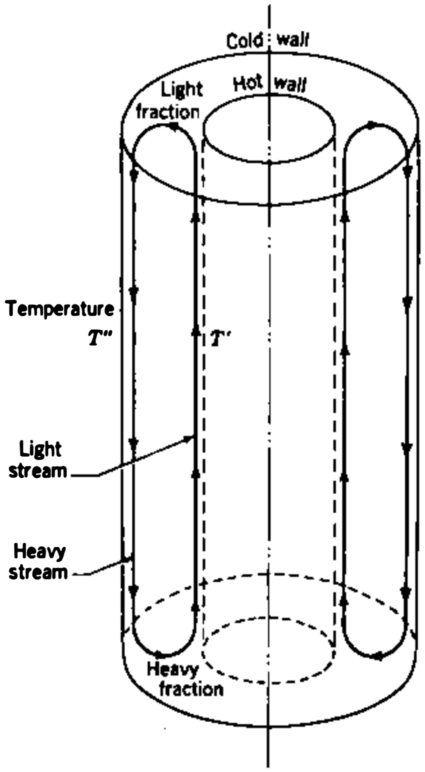


FIGURE C.4 Schematic Diagram of Separation by Thermal Diffusion in a Clusius-Dickel Column.

[SOURCE: Excepted by special permission from *Nuclear Chemical Engineering*, 1957, p. 498. Copyright (c) 1957, by McGraw-Hill, Inc., New York, NY 10020.]

The calutrons were inefficient for uranium enrichment because they could achieve a high degree of separation with only a very low throughput of material. Moreover, the design of the calutrons required batch operation; after a sample of uranium metal was processed, the machines had to be disassembled and the uranium had to be dissolved, recovered, and converted back into a suitable salt to be vaporized at the beginning of the next pass through the calutrons a costly and time-consuming task. Nevertheless, the calutrons played an important role in the Manhattan Project because for nearly a year they were the only uranium isotope separators in operation.

While the Manhattan Project was dependent on the calutrons, efforts were made to boost the production rate of the calutrons by enriching the initial feed of 0.7 percent uranium-235. Even slight improvements, for example, to 1.4 percent, could improve the output of a calutron from one gram per day of 40 percent pure uranium-235 to two grams per day of 80 percent pure product. A second separation process, thermal diffusion, figured in achieving this goal. As shown in Figure C.4, when a temperature gradient is set up in a homogeneous mixture, small diffusion currents arise that conduct one component in the same direction as the flow of heat, and the other in the opposite direction. This thermal diffusion effect was used prior to 1941 to separate isotopes, but application of the effect was hampered by a complete lack of a theory of how the effect might work in liquids, such as UF_6 under pressure. An isotope separation effect in the latter case was discovered in 1940. Although it would have been prohibitively expensive in terms of capital and energy to attempt the complete purification of uranium-235 by thermal diffusion, by 1944 the effect was well enough understood and the need for modest enrichments in feed material for the calutrons was acute, so a large-scale thermal diffusion plant was constructed. During its operation in tandem with the calutrons, it considerably increased the production rate of uranium.

The third source of enriched uranium for the Manhattan Project, and subsequently the sole source of uranium-235 for post-war commercial nuclear industry and weapons programs, relied on a process based on an entirely different principle, gaseous diffusion.

In this process, gaseous UF_6 (the only volatile compound of uranium) is made to flow through a barrier with very fine holes (less than 10 nanometers

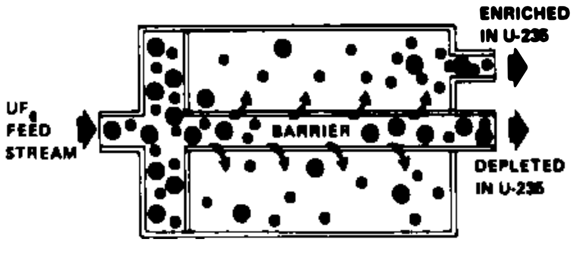


FIGURE C.5 Separation of Uranium Isotopes by Gaseous Diffusion. A gaseous mixture of uranium hexafluoride, containing both uranium-235 and uranium-238 isotopes, will have a uniform distribution of molecules at different kinetic energies. Since kinetic energy is proportional to mass and the square of velocity, an isotope of greater mass will have a smaller mean velocity in the gaseous mixture. Diffusion through a barrier, which is rate-limited by the mean velocity of the gaseous molecule, will preferentially discriminate for lighter isotopes with a higher mean velocity.

[SOURCE: U.S. Department of Energy.]

in diameter) from a high-pressure chamber to a lower-pressure region (Figure C.5). The lighter $^{235}UF_6$ molecules flow through the barrier slightly faster than do the heavier $^{238}UF_6$ molecules; therefore, the gas passing through the barrier is slightly richer in uranium-235 than the portion remaining behind. About one-half of the gas passes through the barrier in any one diffuser unit. The degree of enrichment in a single diffusion operation, though, is quite small the diffusion rates of the two molecules differ by only about 0.4 percent.

To enrich uranium for the first atomic bomb required that the diffusion process be repeated thousands of times by coupling diffuser units in a series arrangement. The extensive recycling of gas through the connected stages required that thousands of times as much material had to pass through the barriers of the lower stages as would ultimately appear as product from the highest stage. Moreover, the gas had to be compressed each time it reentered a stage containing the diffusion barrier, and since pumping this large amount of gas invariably involved heating it, a large cooling system had to be built for the gaseous diffusion plant, as well. With all these complexities, it is no wonder that, when completed, the uranium gaseous diffusion plant in Oak Ridge was the largest industrial plant in the world.

A final separation method that was considered for uranium during the Manhattan Project was the gas centrifuge. Again, the separation factor achievable in a gas centrifuge was close to unity, and the engineering problems associated with constructing and maintaining cascades of thousands of centrifuges operating at high speed were sufficiently formidable that a large-scale production plant was never built.

There can be no doubt that, without the intensive effort put into research on uranium separation processes of all kinds, the Manhattan Project would never have reached a successful conclusion. Yet this effort began in 1941 with the faintest of understandings of the technical and theoretical challenges involved. Clearly, a preexisting knowledge base on the generic principles of isotope separation would have greatly facilitated progress, and provided more plentiful supplies of uranium earlier in the project.

REFERENCES

Styrene—Key Ingredient for Synthetic Rubber

J.C. Frank, G.R. Geyer, and H. Kehde, *Chem. Eng. Prog.*, 65 (2), 1969, 79.

V.C. Smith and W.V. Delnicki, *Chem. Eng. Prog.*, 71 (8), 1975, 68.

G.E. Keller II, Union Carbide Corporation, private communication, 1986.

Penicillin

M. Souders, G.J. Pierotti, and C.L. Dunn, "The Recovery of Penicillin by Extraction with a pH Gradient," in The History of Penicillin Production, A.L. Elder, Ed., *Chem. Eng. Prog. Symp. Series*, No. 100. New York: American Institute of Chemical Engineers, 1970.

W. Podbielniak, H.R. Kaiser, and G.J. Ziegenhorn, "Centrifugal Solvent Extraction," in The History of Penicillin Production, A.L. Elder, Ed., *Chem. Eng. Prog. Symp. Series*, No. 100. New York: American Institute of Chemical Engineers, 1970.

M.C. Brockmann, "Freeze Drying," in The History of Penicillin Production, A.L. Elder, Ed., *Chem. Eng. Prog. Symp. Series*, No. 100. New York: American Institute of Chemical Engineers, 1970.

A.J. Greene and A.J. Schmitz, Jr., "Meeting the Objective," in The History of Penicillin Production, A.L. Elder, Ed., *Chem. Eng. Prog. Symp. Series*, No. 100. New York: American Institute of Chemical Engineers, 1970.

Uranium

H.D. Smyth, Atomic Energy for Military Purposes. Princeton: Princeton University Press, 1946.

M. Benedict and T.H. Pigford, Nuclear Chemical Engineering. New York: McGraw-Hill, 1957.