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CHEMICAL ENGINEERING DIVISION OF AMERICAN SOCIETY FOR ENGINEERING EDUCATION

Graduate Education Issue

FOOD ENGINEERING - De Kee

TRANSPORT PROCESSES - Rosner

ADSUBBLE SEPARATIONS - Lemlich

ENVIRONMENTAL COURSES - Klinzing

DISTILLATION DYNAMICS - Deshpande

ENGINEER AS ENTREPRENEUR - Reynolds

ELECTROCHEMICAL ENGINEERING - Alkire

FUSION REACTOR TECHNOLOGY - Johnson

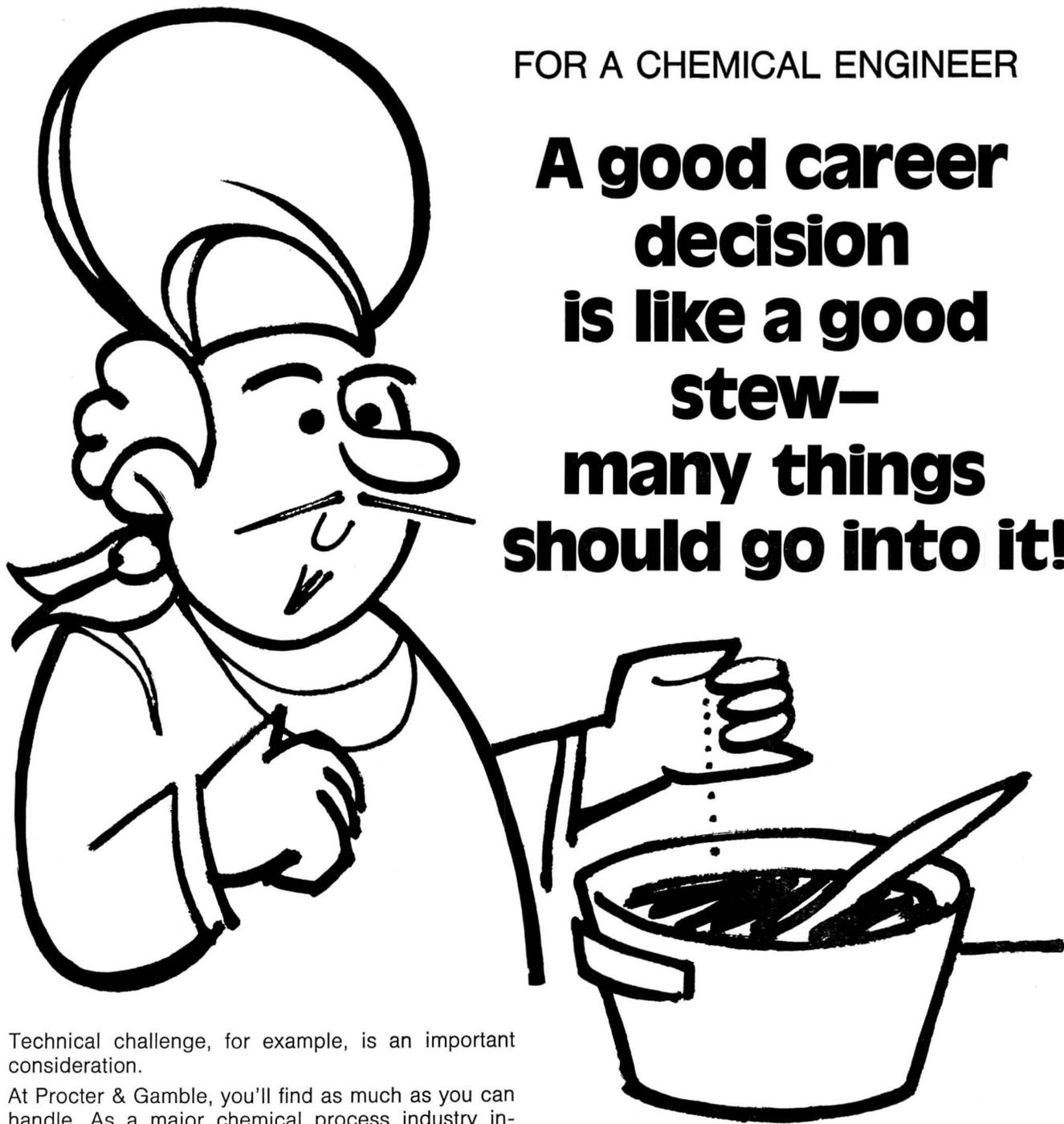
BIOCHEMICAL ENGINEERING - Bailey & Ollis

POLYMER SCIENCE AND TECHNOLOGY - Koutsky

Also:

IMPLEMENTATION OF SI IN ChE—Younquist

1.25-THIS IS A LOG TABLE?—Berty



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NUMBER 4

FALL 1976

GRADUATE COURSE ARTICLES

- 158 Electrochemical Engineering,
Richard Alkire
- 162 Biochemical Engineering Fundamentals
J. A. Bailey and D. F. Ollis
- 166 Food Engineering, *D. De Kee*
- 168 Distillation Dynamics and Control,
Pradeep B. Deshpande
- 172 Fusion Reactor Technology,
Ernest F. Johnson
- 176 Environmental Courses, *G. E. Klinzing*
- 180 Adsorptive Bubble Separation
Methods, *Robert Lemlich*
- 184 Introductory Polymer Science and
Technology, *James A. Koutsky*
- 188 The Engineer as an Entrepreneur—
Some New Concepts, *Howard H. Reynolds*
- 190 Energy, Mass and Momentum
Transport, *Daniel F. Rosner*

DEPARTMENTS

- 155 Editorial
- 154 Letters
- 154, 196 Book Reviews

FEATURES

- 195 Implementation of SI Units in ChE
Education, *Gordon R. Youngquist*
- 198 1.25—This Is a Log Table? *J. M. Berty*
- 200 Index, Volumes VI-X

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REACTION TO GRISKEY RANKING

Sir:

I found the article by R. G. Griskey, "Ranking Chemical Engineering Departments" in the Summer 1976 issue of *CEE* to be very interesting. No doubt he will attract both praise and brickbats for his approach.

With his method a department may fluctuate rapidly in the standing as fortunes go up or down. If a professor lands a million dollar grant, the departmental rating will soar suddenly. If the number of Ph.D.'s produced drops from 15 to 5 in one year (entirely possible) the rating will take a nosedive. I am sure he is quite aware of the short-time fluctuations.

I would like to see ratings compiled every year, by Griskey's scheme. Let me urge him to consider being the author of a yearly ranking for *CEE* or some other journal. To many people it would be as valuable as the annual reviews of special areas of research which were formerly published, for example, by *Ind. Eng. Chem.*

J. W. Westwater
University of Illinois, Urbana

Editor's Reply:

CEE would be interested in receiving another paper from Prof. Griskey on departmental ratings next year, in order to see what, if any, changes have occurred. However, since the results one obtains depend upon the weighting one gives to the various parameters as well as upon the input data, others may want to try a different approach and, in the interest of fairness and diversity, are invited to do so. *CEE* would not want to be thought of as endorsers of any particular rating system or to be more or less committed to publishing the "Griskey Ratings" annually to the exclusion of others.

Other letters will appear in the next issue.

ChE book reviews**HEAT AND MASS TRANSFER DATA BOOK,
2ND EDITION**

by C. P. Kothandaraman and S. Subramanyan
John Wiley & Sons, 1975. \$5.95.

Reviewed by F. J. Lockhart, University of
Southern California

Reference materials, both data and equations, are presented for heat and mass transfer in MKS and SI units.

This book is a compilation of data intended for use with a text-book. There are essentially no discussions of the various tables, graphs and formulae, and at times insufficient definitions of

symbols. References are not given for specific data items, but a list of 16 books is given at the end. So this book is a tertiary reference which does not identify the specific secondary references.

There is no subject index and the table of contents is too brief to be of help in locating specific items of interest. A user will have to prepare his own index. (Perhaps this is a good thing!)

Coverage of heat transfer, physical properties, and fluid flow is thorough. Mass transfer receives scant attention: 2 pages for equation of molecular diffusion, 2 pages for convective mass transfer coefficients, and 3½ pages for humidification equations. □

**MULTIVARIABLE COMPUTER CONTROL
A CASE STUDY**

by D. Grant Fisher and Dale E. Seborg
North Holland Publishing Co. (1976) 205 Pages.

Reviewed by W. Harmon Ray,
University of Wisconsin, Madison

In order to understand the value of this book, one must become familiar with its genesis. Approximately 10 years ago, the Department of Chemical Engineering at the University of Alberta acquired an IBM 1800 process control computer and began interfacing it with equipment in their unit operations laboratory. One of the first units to be put under computer control was a double effect evaporator. In the ensuing years, the authors have used this slightly nonlinear, multivariable evaporator as a model process for testing a wide range of both traditional and modern process control techniques. As their research projects were completed, the results were published in great variety of ways including meeting proceedings, chemical engineering journals, control journals, trade journals, etc. In many instances their work represented the first real time experimental implementation of the techniques applied. After several years of testing and comparing on-line identification, state estimation, and control algorithms applied to this evaporator, quite a number of conclusions could be drawn about the relative merits of the techniques considered. Thus after some urging from their colleagues in the field, the authors were persuaded to compile a case study of process control algorithms applied to the evaporator and to

Continued on page 178.

A LETTER TO CHEMICAL ENGINEERING SENIORS

As a senior you may be asking some questions about graduate school. In this issue CEE attempts to assist you in finding answers to them.

Should you go to graduate school?

Through the papers in this special graduate education issue, *Chemical Engineering Education* invites you to consider graduate school as an opportunity to further your professional development. We believe that you will find that graduate work is an exciting and intellectually satisfying experience. We also feel that graduate study can provide you with insurance against the increasing danger of technical obsolescence. Furthermore, we believe that graduate research work under the guidance of an inspiring and interested faculty member will be important in your growth toward confidence, independence, and maturity.

What is taught in graduate school?

In order to familiarize you with the content of some of the areas of graduate chemical engineering, we are continuing the practice of featuring articles on graduate courses as they are taught by scholars at various universities. Previous issues included articles on applied mathematics, transport phenomena, reactor design, fluid dynamics, particulate systems, optimal control, diffusional operations, computer aided design, statistical analysis, catalysis and kinetics, thermodynamics and certain specialized areas such as air pollution, biomedical and biochemical engineering. We strongly suggest that you supplement your reading of this issue by also reading the articles published in previous years. If your department chairman or professors cannot supply you with the latter, we would be pleased to do so at no charge. But before you read the articles in these issues we wish to point out that (1) there is some variation in course content and course organization at different schools, (2) there are many areas of chemical engineering that we have not been able to cover, and

(3) the professors who have written these articles are not the only authorities in these fields nor are their departments the only ones that emphasize that particular area of study.

Where should you go to graduate school?

It is common for a student to broaden himself by doing graduate work at an institution other than the one from which he receives his bachelor's degree. Fortunately there are many very fine chemical engineering departments and each of these has its own "personality" with special emphases and distinctive strengths. For example, in choosing a graduate school you might first consider which school is most suitable for your own future plans to teach or to go into industry. If you have a specific research project in mind, you might want to attend a university which emphasizes that area and where a prominent specialist is a member of the faculty. On the other hand if you are unsure of your field of research, you might consider a department that has a large faculty with widely diversified interests so as to ensure for yourself a wide choice of projects. Then again you might prefer the atmosphere of a department with a small enrollment of graduate students. In any case, we suggest that you begin by writing the schools that have provided information on their graduate programs in the back of this issue. You will probably also wish to seek advice from members of the faculty at your own school.

But wherever you decide to go, we suggest that you explore the possibility of continuing your education in graduate school.

Sincerely,

RAY FAHIEN, Editor CEE
University of Florida
Gainesville, Florida

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ELECTROCHEMICAL ENGINEERING

RICHARD ALKIRE
University of Illinois
Urbana, Illinois 61801

ELECTROCHEMICAL SYSTEMS usually involve the simultaneous interplay of several different phenomena so that overall behavior is often difficult to predict on the basis of intuition alone. The principles of a rational analysis of electrochemical systems rest upon an understanding of thermodynamics, electrode reaction kinetics, surface phenomena, mass transport and potential field effects. The quantitative basis for electrochemical engineering is the combination of transport phenomena and basic physical chemistry. Since this same combination is included in the training of chemical engineers, it is not surprising that chemical engineers can become familiar with electrochemical systems with relative ease.

The distinguishing feature of electrochemical systems is the electrical potential. The potential plays a fundamental role in the thermodynamics of galvanic cells, theory of solutions of electrolytes, and double-layer effects at interfaces. The potential is important in the kinetics of charge-transfer reactions, in the morphology of surface alterations, and in mass transport by electrical migration. For chemical engineers, there are distinct advantages to having the capability of using electrical energy to carry out chemical reactions. To borrow a metaphor from R. B. MacMullin, [1] "Chemical reaction, like politics, is the art of the possible; electrochemical reaction, like military tactics, is the art of overriding the impossible by applying electrical force." In studying electrochemical systems, the chemical engineer must therefore broaden his traditional scope in physical chemistry, as well as adjust, so to speak, his strategy of attack on engineering problems.

At Illinois, a three hour lecture course in electrochemical engineering (45 class meetings)

is offered every other year. In lieu of using a textbook, we have developed a set of lecture notes and homework problems which have been updated and expanded each time the course has been offered. A reasonable alternative would be to use the thorough, yet concise account of fundamental electrochemical principles as given in *Electrochemical Systems* by John Newman (Prentice-Hall, Englewood Cliffs, N.J., 1973). During the course, about forty homework problems are assigned. These, along with three hour exams, a final examination, and a term paper, determine the course grade. The topic of the term paper is left to the student; grading is based on appropriateness to course material, originality, technical proficiency, thoroughness of coverage, and accuracy in communication. Some topics covered in recent years include desalination, hydrometallurgy, waste water treatment, recovery of heavy metals, industrial energy conservation, electro-organic synthesis, batteries and fuel cells, and various aspects of corrosion.

In addition to chemical engineers, the course has included graduate students from ceramic, metallurgical, nuclear and mechanical engineering, electroanalytical and physical chemistry, and solid-state physics.

LECTURE TOPICS

AN OUTLINE OF LECTURE topics is given in Table I. A bibliography of useful source material for the preparation of lectures on various topics is available from the author upon request. The introductory comments include a voltage balance about a cell in order to indicate the different phenomena which act to consume the voltage applied to the cell terminals. The voltage balance includes terms associated with the thermodynamic potential of the cell at rest, and overpotentials which arise at the electrode surface (charge transfer and crystallization processes, etc.), in the mass transfer zone near the surface

(concentration variations) and the remaining regions within the cell (ohmic resistance effects). The voltage balance indicates that consideration must be given to thermodynamic, kinetic, mass transport, and potential field effects.

Of the various phenomena which contribute terms to the voltage balance, the notion of ohmic resistance is the most familiar to chemical engineers owing to similitude with heat and mass conduction, and potential flows. The physical chemistry of conduction processes is reviewed for aqueous, nonaqueous, fused salt and solid-state electrolyte systems. The purpose is not to teach fundamental physical chemistry, but to provide sufficient understanding of these systems to permit estimation of conduction parameters for use in engineering applications. Finally, the notion of the spatial distribution of potential and current is introduced in order to calculate the ohmic resistance of an electrolytic solution between two electrodes. Examples discussed at this point can be drawn from applications in electroplating, aluminum cell design, and electro-organic synthesis cell design.

The final discussion topic brings economic factors (dollar balances) into the models in order to provide a quantitative approach to process optimization. Numerous tradeoffs can be decided as, for example, number of individual cells, optimum cell current and electrode area, best anode-cathode gap spacing, frequency of gap adjustment, etc.

Principles of thermodynamics of galvanic cells are developed next, with examples which include fused salt and solid-state cells. The thermodynamic interactions between heterogeneous charge transfer reaction and homogeneous chemical reactions is covered in detail (Pourbaix diagrams) in preparation for future discussion of corrosion systems. It is, of course, crucial to establish a consistent set of nomenclature for potential signs, and the IUPAC system is used here. Application of principles is made in the areas of estimating cell voltages and measuring thermodynamic functions.

The kinetics of electrode processes are approached by first introducing the use of reference electrodes and power supplies, by means of which



The author studied electrochemical engineering under Professor Charles Tobias at Berkeley, and Professor Carl Wagner at the Max Planck Institut für physikalische Chemie at Göttingen. On the faculty of the University of Illinois since 1969, Alkire has carried out a program of fundamental research which has had applications in electroplating, corrosion, batteries, copper electrowinning, electro-organic processing, and cell design.

the reaction rate and reaction driving force can be measured simultaneously in order to determine the rate constant. In order to analyze the data properly, the existence of the electrical double layer is introduced with discussion of double layer phenomena in colloidal suspension, electrophoretic separation, streaming currents, and electropainting. Then the theory of kinetic rate processes is applied to heterogeneous charge transfer reactions in order to generate the form of a reaction rate expression for simple and multiple-step reaction sequences. Since chemical engineers are not accustomed to the notion of an electrical potential acting as a driving force for a reaction, it is especially important to proceed with caution in this area. The role of electrode kinetics on mixed-potential (uniform corrosion) systems receives careful attention.

ENGINEERING RAMIFICATIONS

AT THIS POINT, it seems worthwhile to shift attention to some of the engineering ramifications of the fundamentals introduced so far. In particular, the relative importance of charge-transfer resistance to ohmic resistance (defined by the dimensionless polarization parameter) is of great importance in determining the uniformity of the current distribution along an electrode surface. The polarization parameter provides one basis for engineering scale-up of electrochemical systems. The difficulty of scale-up is central to

TABLE I: Course Outline

PRINCIPLES OF ELECTROCHEMICAL ENGINEERING

- I. Introduction to Electrochemical Engineering
 - A. The scope of electrochemical phenomena
 - B. Disciplines which encounter these phenomena
 - C. Introductory concepts, Faraday's laws
- II. The Electrolytic Phase
 - A. Conduction processes in aqueous solutions
 - B. Conduction in nonaqueous solutions and fused salts
 - C. Conduction in ionic crystals
 - D. The resistance of electrolytic solution between electrodes: potential field distribution
- III. Thermodynamics of Galvanic Cells
 - A. Electromotive force
 - B. Concentration cells and transference
 - C. Applications of galvanic cells
 - 1. Measurements of Gibbs energy, activity coefficients, standard potentials, ionization constants; monitoring of chemical reactions on electrode surfaces
 - D. Application of standard potentials
 - 1. Criteria for a stable interface, cell reactions at stable interfaces, Pourbaix diagrams, corrosion
- IV. Kinetics of Electrode Processes
 - A. Reference electrodes
 - B. Power sources
 - C. Structure of the electrical double layer
 - 1. Capacitance, charging and faradaic reaction, stability of colloidal suspensions, applications
 - D. Charge transfer
 - 1. Theory of rate processes, influence of concentration variation, complex reaction sequences, methods of measurement of rate constants
 - E. Applications
 - 1. Corrosion: mixed potential theory, cathodic protection; the polarization parameter and current distribution phenomena, electroplating, battery electrodes
- V. Mass Transport in Electrochemical Systems
 - A. Electrolysis under diffusive transport control
 - 1. Steady and unsteady-state methods of electroanalytical chemistry
 - B. Electrolysis under convective transport control
 - C. Current distribution at the limiting current
 - D. Current distribution below the limiting current
- VI. Synthesis of Fundamentals
 - A. Survey of applications
 - B. Modeling electrochemical systems
 - C. Developing an electrochemical process
 - D. Optimizing electrochemical processes

the task of electrochemical engineering, and will be developed to a considerable extent later in the course. Applications of the polarization parameter are given by examples of designing battery plates, and electroplating systems.

Although mass transport is familiar ground to chemical engineers, the role of the potential and cell voltage present unfamiliar new territories which must be worked through. Simple one-dimensional examples are available in many of the methods employed in electroanalytical chemistry. More complex examples involve convective mass transport wherein the current and potential distribution along an electrode is not uniform owing to the presence of a nonuniform mass transfer boundary layer.

The course now moves from providing a fundamental background to developing the engineering prowess needed for handling practical situations. This last group of lectures is, I feel, the heart of the course. First, a survey of existing industrial process technology is presented in order to show how closely related is the process chemistry and the process engineering. Copper electrorefining, chlorine-caustic production, aluminum reduction, battery and fuel cell systems, and water electrolysis provide fertile grounds for discussion. In copper refining cells, for example, a change in process temperature affects the electrolyte conductivity, the electrochemical reaction rate constant, the solubility of dissolved salts and the current efficiency. From such examples, the

The purpose is not to teach fundamental physical chemistry but to provide sufficient understanding of these systems to permit estimation of conduction parameters for use in engineering applications.

students gain a fuller sense of the complex relation between process variables and process behavior.

The next topic is to show how to develop mathematical models to correlate the behavior of an electrochemical system with the parameters, or process variables of the system. The discussion covers the justification of modeling activities, the different goals and levels of sophistication which models may take on, the typical simplifications which are commonly invoked, and the complexities

For chemical engineers there are distinct advantages to having the capability of using electrical energy to carry out chemical reactions. To borrow a metaphor from R. B. McMullin, "chemical reaction, like politics, is the art of overriding the impossible by applying electrical force."

which often limit such endeavors. Based upon my own interests, I have used as examples models of flow-through porous electrodes, circuit board fabrication, and localized corrosion.

The third step is to evaluate and work up the process engineering for a reaction which has been studied in the research laboratory at the beaker scale. Although many examples are probably available, the workup of the Baizer process for adiponitrile production is particularly well documented insofar as it was awarded the 1965 Kirkpatrick Award for Chemical Engineering Achievement. Attention centers on having students anticipate (1) what dilemmas must be solved in order to settle upon the choice of system chemistry and process operating conditions and (2) when and how to use models to assist in determining what effects are important and how they will scale-up.

The final discussion topic brings economic factors (dollar balances) into the models in order to provide a quantitative approach to process optimization [2]. Numerous tradeoffs can be decided as, for example, number of individual cells, optimum cell current and electrode area, best anode-cathode gap spacing, frequency of gap adjustment, etc.

By discussing the foregoing engineering examples, a great deal can be accomplished in dispelling the aura of black magic which electrochemical systems seem to possess.

CONCLUDING REMARKS

OF THE TOTAL POWER generated in the United States, nearly 10% is consumed by the electrochemical process industry. Meanwhile, corrosion processes consume more than fifteen billion dollars in U. S. resources each year, or 1¼% of the GNP. Owing to the power consumption and economic importance of the electrochemical industry, there is certainly no doubt about the technological importance of electrochemical phenomena, nor about the economic incentives for improving our engineering knowledge

of electrochemical systems, including corrosion systems.

Compelling trends toward the future indicate that it will become even more important to understand electrochemical systems. Within the next twenty-five years, the primary form of energy will shift to an electrical form, away from the present chemical fossil fuel form. Nuclear and solar generation both require energy conversion and storage capabilities, and electrochemical routes are certainly most viable.

Perhaps even more importantly, chemical engineers will have to learn to operate chemical processes without a fossil fuel based economy. Electrical energy will become increasingly inexpensive in comparison with chemical agents for oxidation and reduction operations. Therefore, it seems only reasonable that chemical engineers will give increased consideration to the evaluation of electrochemical routes for the synthesis of chemical materials and for the beneficiation of increasingly lean natural resources.

It is with these perceptions of the future that the choice of examples and discussion topics is made in our teaching efforts. □

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2. T. R. Beck, "Industrial Electrochemical Processes" in *Techniques of Electrochemistry*, Vol. III, Yeager and Salkind, Wiley-Interscience, N.Y., 1976.

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MICROBIAL AND ENZYMATIC activities have been an intimate part of man's history. Microbes probably account for greater than ninety percent of all animal mass; their biochemical action contributes significantly to chemical processes found in agriculture, diseases, digestion, antibiotic production, food manufacture and processing, spoilage, sanitation, waste disposal, and marine and soil ecology. Consequently, it is remarkable that the study of biochemical processes is not an established component of chemical engineering education.

One factor which seems to contribute to the neglect of biochemical engineering courses in many departments presently is the tendency in current texts and monographs to concentrate on a particular class of applications such as fermentations, enzyme utilization or wastewater

When confronted with many pages of descriptive text on biochemistry and microbiology, . . . overcoming student apprehension is perhaps the greatest challenge in teaching the course.

treatment. While each such topic is important, it appears that only a course aimed at all aspects of biochemical engineering applications is likely to provide a sufficiently broad learning base to justify incorporation into most ChE curricula.

We have minimized this problem in our course by stressing underlying common fundamentals

and a very broad range of applications. The fundamentals comprise those particular topics which profoundly influence the behavior of man-made or natural microbial or enzyme reactors. Such biological examples include the dependence of enzyme (and thus microbial) activity on substrate concentration, pH, temperature, and ionic strength, the existence of a small number of important metabolic paths among the multitude of microbial species, the cellular control mechanisms for complex internal reaction networks, and molecular devices for biological information storage and transmittal. Useful topics chosen from chemical and engineering sciences are the energetics of isothermal, coupled reactions; mixing; transfer of heat and molecular solutes; ideally and imperfectly mixed chemical reactors; and filtration.

The general character of these fundamentals is subsequently stressed by applications to class examples and a wide variety of homework problems. These latter exercises include analyses of spectrophotometry, desugaring of egg white, silver recovery from photographic film, exotoxin production, enzyme electrodes, home winemaking, chlorination disinfection, detergent biodegradation, steam reaeration, anaerobic digester heat balances, production of optically pure amino acids, and soil nitrification.

A second resistance in some of the previous efforts in biochemical engineering education arises from the assumption of significant *a priori* background in the biological sciences. Many ChE students have not studied biochemistry and microbiology, yet a working familiarity with both fields is necessary in biochemical engineering. Consequently, about thirty percent of our course is devoted to a rapid survey of those elements of microbiology and biochemistry essential to understanding biochemical reactors. It is assumed at the outset that the student is unfamiliar with both topics.

During the presentation of this material, an attempt is made to relate life sciences funda-

mentals to their process implications. For example, following discussion of molecular genetics, viruses, mutation, and genetic manipulation, we investigate recent applications of microbial genetics in developing especially productive microorganisms for several fermentation processes. Searches for explanations of the improved characteristics of the mutated microbes quickly leads to consideration of metabolic control systems and membrane transport, areas which have also been examined earlier in the course.

Obviously there is an alternative to our approach: require the students to take regular courses in the biological sciences before entering

Many ChE students have not studied biochemistry and microbiology . . . Consequently, about thirty percent of our course is devoted to a rapid survey of those elements of microbiology essential to understanding biochemical reactors.

the biochemical engineering course. In what are already crowded curricula, imposition of such prerequisites greatly limits the students' opportunity to study biochemical engineering, and only those students actively engaged in research in the area are likely to elect such a sequence. On the other hand, by presenting biological fundamentals integrated with engineering analyses, design principles, and applications in a single course, the subject is easily accessible to any graduate student, and indeed to any interested upper level undergraduate. Following this course, those students concentrating in biochemical engineering can and should broaden their base in the life sciences through additional, more advanced courses taught in biochemistry, microbiology, biophysics, and other related departments.

The course is summarized in Table 1. The material progresses from atomic to macroscopic dimensions; i.e., from molecular through cellular to microbial population dynamics. Applications and the associated engineering design and analysis principles are presented as soon as the necessary background life science material has been covered. Thus, enzyme isolation and applications are considered before discussion of cell metabolism, and pure culture fermentations are examined before delving into the complexities of multiple species

interactions and associated applications.

With this parallel approach, the molecular→cellular→population paradigm is maintained throughout the lectures in fundamentals and applications, description and analysis.

TEACHING THE COURSE

THE COURSE HAS BEEN taught in both a single quarter and a single semester format. In order to allow coverage of all elements of the outline during this period, an extensive set of notes has been developed so that many topics can be presented in the form of outside reading assignments. Besides their use in the courses at Houston and Princeton, all or portions of these notes have been used in biochemical engineering courses at the University of California at Berkeley, Iowa State University, the University of Maryland, and the University of Virginia. A textbook derived from these notes is now in press.

We have noted that engineering students may become a bit disoriented when confronted with many pages of descriptive text on biochemistry and microbiology, each introducing one or more new terms in an expanding cascade of new vocabulary. Overcoming this student apprehension is perhaps the greatest challenge in teaching the course, and we have used a variety of strategies in concert to ameliorate the problem.

First, diversions from the onslaught of new biological concepts and terminology are provided in both local and longer scales in the lectures and notes. The best example of the latter case is the location of topics III and IV in the course outline. In addition to the reasons given earlier, the presence of these topics in the midst of biological basics provides the engineering student a respite in the relatively familiar territory of kinetics, transport-reaction interaction, and commercial processes. Moreover, these topics show the student that the biochemistry from topic II is indeed necessary and useful, and thus motivation is instilled for digging into energetics, metabolism, and genetics in topics V and VI.

Also, practical implications of basic concepts are briefly indicated during the fundamentals discussions. One example of this approach has already been mentioned; another is the discussion of the influence of iron ion on the citric acid fermentation in conjunction with the presentation of the tricarboxylic acid cycle. At this point previous consideration of enzyme cofactor effects can also be recalled and put into a commercial process

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perspective. Worked examples interspersed in the course serve a similar function of breaking up the new biological material. Finally, homework exercises on all topics have been prepared, and these are regularly assigned (a collection of problems is available from the authors upon request). Combined with frequent quizzes, these provide the engineering student with regular opportunities to attempt quantitative analyses. Besides their obvious important pedagogical role, these exercises also alleviate the "culture shock" (!) of facing many new biological terms and concepts. □

TABLE 1: COURSE OUTLINE

Biochemical Engineering Fundamentals

I. A LITTLE MICROBIOLOGY

- A. Biophysics and the Cell Doctrine
- B. The Structure of Cells (procaryotic cells; eucaryotic cells, cell fractionation) (Example: Analysis of particle motion in a centrifuge)
- C. Important Classes of Microbes (bacteria; yeasts; molds, algae and protozoa)

II. CHEMICALS OF LIFE

- A. Lipids (fatty acids; fat-soluble vitamins; steroids) Example: Modification of biomembrane permeability
- B. Sugars and Polysaccharides
- C. From Nucleotides to RNA and DNA (coenzymes; RNA, DNA)
- D. Amino Acids into Proteins (polypeptides; protein structure; biological regulation)
- E. The Hierarchy of Cellular Organization

III. THE KINETICS OF ENZYME-CATALYZED REACTIONS

- A. The Enzyme-Substrate Complex and Enzyme Action
- B. Simple Enzyme Kinetics with One and Two Substrates (Michaelis-Menten kinetics; two-substrate reactions and cofactor activation)
- C. Determination of Elementary Step Rate Constants (pre-steady-state, relaxation kinetics)
- D. Other Patterns of Substrate Concentration Dependence (activation; inhibition; multiple substrates)
- E. Modulation and Regulation of Enzymic Activity
- F. Other Influences on Enzyme Activity (pH, temperature, mechanical forces)
- G. Enzyme Reactions in Heterogeneous Systems (insoluble substrates; immobilized enzymes)

IV. ISOLATION AND UTILIZATION OF ENZYMES

- A. Production of Crude Enzyme Extracts
- B. Enzyme Purification (chromatography; dialysis; solid phase syntheses)
- C. Enzyme Immobilization
- D. Application of Hydrolytic Enzymes (esterases, carbohydrases, proteases)
- E. Other Enzyme Applications (medical, new technology)
- F. Immobilized Enzyme Technology (industrial processes; medical and analytical applications; utilization and regeneration of cofactors)
- G. The Scale of Enzyme Technology

V. METABOLIC PATHWAYS AND ENERGETICS OF THE CELL

- A. The Concept of Energy Coupling: ATP and NAD
- B. Anaerobic Metabolism: Fermentation (glycolysis; other pathways)
- C. Respiration and Aerobic Metabolism (TCA cycle; respiratory chain; partial oxidation; regulation)
- D. Photosynthesis: Tapping the Ultimate Source (Calvin Cycle; chloroplasts)
- E. Biosynthesis (ATP utilization; small molecules; macromolecules)
- F. Transport Across Cell Membranes (passive, facilitated, active transport) (Example: Transport of nitric acid through a liquid membrane)

VI. CELLULAR GENETICS AND CONTROL SYSTEMS

- A. Molecular Genetics (DNA translation; replication; mutation; induction; repression)
- B. Growth and Reproduction of a Single Cell (synchronous culture; E. coli cell cycle; eucaryotic cell cycle)
- C. Alteration of Cellular DNA (viruses, phage; transformation, conjugation; composite DNA)
- D. Commercial Applications of Microbial

Genetics and Mutant Populations (Implications for medium formulation; auxotrophic mutants)

modeling and optimization for production of α -Galactosidase by a *Monascus* sp. mold)

VII. KINETICS OF SUBSTRATE UTILIZATION, PRODUCT YIELD, AND BIOMASS PRODUCTION IN CELL CULTURES

- A. Growth Cycle Phases for Batch Cultivation (lag phase; exponential growth, the Monod equation; stationary and death phase)
- B. Mathematical Modeling of Batch Growth (reaction networks; structured, unstructured models; mold growth)
- C. Product Synthesis Kinetics (fermentation classifications; Shs segregated model)
- D. Overall Kinetics in Cases of Reaction-Mass Transport Interaction (lumped, distributed models for cells, flocs, mold pellets)
- E. Thermal Death Kinetics of Cells and Spores

VIII. TRANSPORT PHENOMENA IN MICROBIAL SYSTEMS

- A. Gas-Liquid Mass Transfer in Microbial Systems (basic concepts; metabolic oxygen utilization rates) (Example: Effectiveness factor of a microbial monolayer)
- B. Determination of Oxygen Transfer Rates (gas-liquid reactions; dissolved oxygen measurements) (Examples: Warburg respirometer; electrochemical determination of $k_L a$)
- C. Mass Transfer for Freely Rising or Falling Bodies
- D. Mass Transfer Across Free Surfaces
- E. Forced Convective Mass Transfer (key dimensionless groups; mass transfer coefficient correlations)
- F. Surface Area Correlations for Mechanically Agitated Vessels
- G. Other Factors Affecting $k_L a$ (diffusivities; ionic strength; surface active agents)
- H. Non-Newtonian Fluids (models; suspensions; power consumption mass transfer)
- I. Scaling of Mass Transfer Equipment
- J. Particulate Mass Transfer: Filtration (single fiber efficiencies; mass transfer coefficients)
- K. Heat Transfer (microbial heat generation; heat transfer correlations)

IX. BIOLOGICAL REACTOR DESIGN AND ANALYSIS

- A. The Ideal Continuous Flow Stirred Tank Reactor (Monod's chemostat; incomplete mixing, films, recycle effects; enzyme catalyzed reactions) (Example: Agitated CSTR design for a liquid hydrocarbon fermentation)
- B. Residence Time Distributions (measurements; applications)
- C. Tubular and Tower Reactors (ideal plug flow tubular reactor; tower reactors; tanks-in-series and dispersion models)
- D. Sterilization Reactors (batch; continuous)
- E. Relationships Between Batch and Continuous Biological Reactors (Example: Reactor

X. BIOLOGICAL REACTORS, SUBSTRATES, AND PRODUCTS I: SINGLE SPECIES APPLICATIONS

- A. Fermentation Technology (medium formulation; aseptic practice; cell harvesting, product recovery)
- B. Product Manufacture by Fermentation (brewing and wine making; oxidative transformations; organic, amino acids; complex molecules: gibberelins, vitamins, antibiotics; undesirable products) (Example: Reaction rates in microbial films; temperature programming for optimal penicillin production)
- C. Reactors for Biomass Production (food; food processing; agricultural applications; immunology, tissue culture, and "Vaccine" production) (Examples: A batch growth model for liquid hydrocarbon fermentations; production of a low-intermediate molecular weight product; cell growth and virus propagation kinetics in tissue culture)

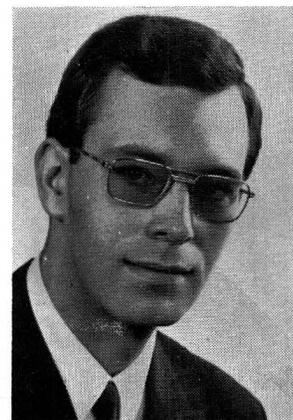
XI. ANALYSIS OF MULTIPLE, INTERACTING MICROBIAL POPULATIONS

- A. Neutralism, Mutualism, Commensalism, and Ammensalism
- B. Mathematical Preliminaries (Example: Two-Species dynamics near a steady state)
- C. Competition: Survival of the Fittest
- D. Predation and Parasitism (Lotka-Volterra model; other one predator-one prey models) (Example: Model discrimination and development via stability analysis)
- E. Effects of the Number of Species and their Web of Interactions (trophic levels, food chains, food webs; mass action models; qualitative stability; randomly constructed food webs) (Examples: An application of the mass action theory; qualitative stability of a simple food web)
- F. Spatial Patterns

XII. BIOLOGICAL REACTORS, SUBSTRATES, AND PRODUCTS II: MIXED MICROBIAL POPULATIONS IN APPLICATIONS AND NATURAL SYSTEMS

- A. Uses of Well-Defined Mixed Populations (Example: Enhanced growth of methane-utilizing *Pseudomonas* sp. due to mutualistic interactions in a chemostat)
- B. Spoilage and Product Manufacture by Spontaneous Mixed Cultures
- C. Microbial Participation in the Natural Cycles of Matter and Energy
- D. Biological Wastewater Treatment (wastewater characteristics; activated sludge process; trickling biological filters; anaerobic digestion) (Example: Simulation studies of control strategies for anaerobic digesters)

FOOD ENGINEERING



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The dramatic changes in the world population activated intensive interest in food problems all over the world.

As a result, our department began offering a selected topics type of course dealing with some aspects of food engineering; indeed, the volume of information available in the field is enormous and a one semester course can never cover more than a small fraction of the material.

TABLE I: FOOD ENGINEERING COURSE OUTLINE

PART I: BIOCHEMISTRY AND MICROBIOLOGY

- A. Amino acids
- B. Proteins
- C. Bacteria
- D. Yeasts
- E. Microbial growth curve

PART II: OIL SEED TECHNOLOGY

- A. Preparation of beans
- B. Extraction
- C. Desolventizing
- D. Lecithin separation
- E. Alkali refining
- F. Bleaching
- G. Hydrogenation
- H. Deodorization
- I. Mixing
- J. Rheology

PART III: BIOCHEMICAL ENGINEERING

- A. Sterilization
- B. Fermentation Kinetics
- C. Batch and CSTR reactors
- D. Application to the brewing industry

PART IV: STUDENT PRESENTATION OF TERM PAPERS

1. Food from petroleum
2. Food additives
3. Food processing by microwaves
4. Protein from grasses

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The course was offered for the first time to fourth year students and to first level graduate students in chemical engineering. Chemists and microbiologists also took the course but were somewhat disappointed due to their lack of knowledge in kinetics, transport phenomena, unit operations and mathematics.

Active student participation was promoted by including assignments in which judgement and ingenuity were to be exercised and alternative solutions considered, followed by oral presentation of a term paper, movie projections and a final quiz.

We hope that the program of the course will captive one's intellectual interest and indicate important ways in which chemical engineers can broaden their services to humanity.

DISCUSSION OF COURSE MATERIAL

TABLE I OUTLINES the course material. The first two sections of the first part introduced the student to biochemistry. Properties of amino acids and protein structures were discussed in detail. The effect of processing factors such as heat, storage, etc . . . on the structure of protein was dealt with and some of the analysis methods (chromatography X-Ray diffraction) were introduced. Then followed some notion of microbiology. In addition to a general discussion about the cell, some properties of bacteria and yeasts were focussed upon. References [1-7] were very helpful in this context. The second part of the course

switched the student back into the engineering world of material balances, mass transfer and transport phenomena. As an example, the production of margarine was discussed in detail. Attention was given to equipment selection (cracking mills, extraction apparatus etc.), calculations were made on extraction, mixing and hydrogenation. With regard to those subjects, references [8-9, 13-14, and 15] were of particular interest.

Some time was spent on the problems encountered with the choice of solvent(s) and on efficiency calculations based on film theory and on diffusion theory [12]. Due to time limitation, the previous part was followed by a too brief introduction to the rheology of non-Newtonian liquids [16-17]. This second part was then concluded by a projection of the two following movies:

- Raw materials and refining vegetable oils and fats.
- What is margarine, vegetable oils and fats.

These movies were produced for the Lever (British) Company by Worldwide Incorporated and rented from the Canadian Film Institute, Ottawa, Canada. References [10-11] proved also to be of interest in the preparation of this material.

The dramatic changes in the world population activated intensive interest in food problems all over the world. As a result, our department began offering a course dealing with some aspects of food engineering.

At various appropriate points in the third part of the course, several aspects of the beer brewing industry were introduced. Sterilization was looked upon from an engineering point of view. In addition to presenting the classical Michaelis-Menten kinetic model, we attempted to develop more sophisticated ones such as the Aiyar and Luedeking [21] and Kono-Asai [25] models.

Material and energy balances were then used to predict the performance of batch reactors. Continuous systems were next studied; here a variety of situations was looked into, such as the case of a series of vessels, a single vessel with recycling and the washout problem [18-19] other fermentations were presented, dealing with the given models [22, 24]. In addition to the above mentioned references the following publications

proved to be useful in connections with this design part: [20, 23, 26]. The course was concluded by the presentation of the term papers. Table II shows the chosen topics. □

TABLE II: TERM PAPER TOPICS

1. Food from petroleum
2. Food additives
3. Food processing by microwaves
4. Protein from grasses
5. Protein from algae
6. Enzymes and the tenderization of meat
7. Gibberellin fermentation
8. Control of fermentation processes
9. Sugar refining
10. Sorbitol utilization
11. Liquorice in food
12. Yeast as an animal food
13. Ethanol from wood
14. Protein from spent sulphite liquor
15. Furfural production from bagasse
16. Products from molasses
17. Starch

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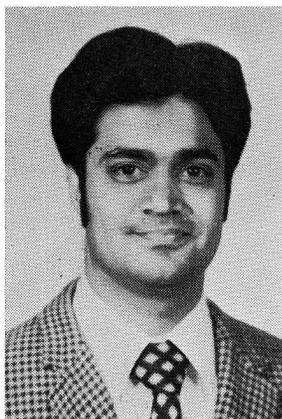
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Continued on page 174.

DISTILLATION DYNAMICS AND CONTROL

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A TYPICAL UNDERGRADUATE curriculum in chemical engineering includes courses in unit operations, process design, and process control. In the first of these, a number of unit operations, e.g., distillation, absorption, extraction, are studied. In distillation, the following topics are usually covered: vapor-liquid equilibria, heat and material balances as applied to multistage columns, determination of the number of stages required for the specified separation of a binary mixture, reflux ratio requirements, and the efficiency of distillation columns. The detailed steady-state design of towers is taken up in



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process design. The third course, process control, introduces the student to the instrumentation used for the measurement, manipulation, and control of process variables. He learns the Laplace-transform methods for the characterization of processes, measuring elements, controllers, and final control elements. This is followed by the study of frequency response techniques for the design of control systems. Finally, criteria needed to determine the stability of control systems are discussed.

A graduate student with a background in the above courses usually has available to him an advanced course in distillation, which covers topics in multicomponent separations. Thus, he gets a fairly extensive background in the steady-state process design and operation of distillation columns. However, he has relatively little background in the automatic control of towers. For the student who may seek an industrial career in the area of distillation, or for one who plans advanced graduate work in distillation, it is believed that a gap exists which needs to be filled. It was with this in mind that a graduate level course entitled "Distillation Dynamics and Control," was developed. This course has been offered once to a class composed of 12 students, of whom 2 are Ph.D. students, 6 M.S. students (including 4 part-time students from industry), and 4 M. Eng. students. The reaction of the students to the course has been favorable.

COURSE CONTENT

THE SUGGESTED TOPICS for this course are shown in Table I. There are two ways in which this course can be taught. (1) If the curriculum structure, number of students available, and faculty loads are such that only one course can be offered in the area of distillation, the topics in Table I can be supplemented with steady-state topics. This means that some of the control topics would have to be eliminated, or

only briefly covered. (2) If desired, the entire course can be devoted to control topics. In this case, the course will benefit if it is supplemented with distillation control experiments which demonstrate the operation of control schemes. This approach can also utilize digital computer programs to validate some of the concepts listed in Table I. The course as taught here did include steady-state topics, but did not cover Parts VII-B, VIII-B, and IX. However, when the distillation controls laboratory becomes operational, it is contemplated that the entire course will be devoted to control topics. The course description in this article follows the latter approach.

One of the first questions that a control engineer has to address himself to is: "how many variables are available for control?" In order to answer this question, one must consider the analysis of the "degrees of freedom," in which the system equations are developed and compared with the number of unknown variables in order to decide how many variables are available for control, (Part II). Part III-A develops a basis for the control of one or both product compositions. The material balance and the separation factor, S, for a binary tower can be expressed, respectively, as

$$\frac{D}{F} = \frac{Z_F - X_B}{X_D - X_B} \quad (1)$$

$$S = \frac{X_D (1 - X_B)}{X_B (1 - X_D)} = f(V/F, n, \alpha) \quad (2)$$

where

Z_F, X_D, X_B = composition of the more volatile component in the feed, distillate and, bottoms, respectively, dimensionless

D = distillate rate, $\frac{\text{moles}}{\text{time}}$

F = feed rate, $\frac{\text{moles}}{\text{time}}$

V = vapor boilup in reboiler, $\frac{\text{moles}}{\text{time}}$

n = no. of theoretical stages

α = relative volatility, dimensionless

For a fixed column operating with a given binary mixture, Equation (2) reduces to

$$S = \frac{X_D (1 - X_B)}{X_B (1 - X_D)} = f(V/F) \quad (3)$$

Equations (1) and (3) can be considered together

TABLE I. COURSE OUTLINE

DESCRIPTION	SUGGESTED REFERENCES
I. Introduction	
A. Review of Steady-state Distillation Concepts	
B. Introduction to Automatic Control of Distillation Columns	
II. "Degrees of Freedom Analysis" to Determine the Number of Variables Available for Control	(1) pp. 69-75 (2) pp. 355-65
III. Material Balance Control Schemes	
A. Manipulation of Material Balance and Heat Input	(3) pp. 288-305
B. Pressure Control Methods	(3) pp. 299-302
C. Criteria for Sensor Location	(2) pp. 476-82
D. Control Strategy Analysis on McCabe-Thiele and Ponchon-Savarit Diagrams	(1) pp. 334-39 (2) pp. 417-27 (4) pp. 139-44 (5) pp. 26-29
IV. Dynamic Mathematical Modeling and Simulation of Distillation Columns	
A. Binary and Multicomponent Systems	(1) pp. 69-80
B. Open-Loop and Closed-Loop Responses	(1) pp. 148-59
V. Frequency Response Methods for Control Systems Design	
A. Linearized Models	(1) pp. 267-76
B. Experimental Methods — Pulse Testing	(1) pp. 282-93
VI. Control Over Both Products	
A. The Interaction Problem in Multivariable Control and Bristol's Interaction Measure	(6) pp. 133-34 (3) pp. 188-98
B. Proper Pairing of Variables and Application in Distillation	(3) pp. 305-06 (7) pp. 403-07 (8) pp. 227-36 (9) pp. 52-57
C. Design of Decouplers	(1) pp. 380-84 (10) pp. 198-203
VII. Advanced Control Schemes for Distillation Columns	
A. Feedforward Control	(1) pp. 431-37 pp. 445-47 (11) Tabs 1-4
B. Inferential Control	(12) pp. 614-23; (13) (14) pp. 127-31
VIII. Special Problems	
A. Inverse Response in Distillation Columns	(1) pp. 377-80 (15)
B. Override Control Schemes	(1) pp. 342-44 (16)
IX. Control Instrumentation	
A. Sensors, Controllers, and Control Valves	(1) pp. 305-45 (3) pp. 61-123

for deciding which streams should or need be manipulated in order to control one or both product compositions. Although the development is based on a binary column, the principles may be extended to multicomponent distillation.

In order to exercise proper control, it is essential that column pressure be maintained constant. Therefore, the methods for varying the rate of condensation so as to control column pressure are discussed next in Part III-B.

A graduate student usually gets a fairly extensive background in the steady-state process design and operation of distillation columns. However, he has relatively little background in the automatic control of towers.

Although the objective of most control schemes is to control product compositions, composition analyzers are not widely used for control purposes for reasons of cost and long time-lags. Instead, temperatures at appropriate locations in the column are controlled so as to indirectly control product quality. Thus, it is appropriate at this point to discuss the criteria for the suitable location of temperature sensors (III-C).

Although limited in its concepts to the distillation of binary mixtures, the McCabe-Thiele and Ponchon-Savarit diagrams are helpful in analyzing the effect of various upsets on the composition of product streams. The control strategy analysis on these diagrams is the subject of discussion in Part III-D.

Part IV is concerned with dynamic mathematical modeling and digital simulation of distillation towers for separating binary and multicomponent mixtures. The purpose here is to evaluate the open-loop response and the closed-loop response of columns (with specified control schemes), to various upsets. The dynamic models of towers and the associated equipment are developed and the system equations are solved on the digital computer in order to obtain open-loop and closed-loop responses.

CONTROLLER SYNTHESIS

PART V DEALS WITH controller synthesis; analytical and experimental approaches are covered. In the former approach (V-A), the mathematical model developed earlier is linearized,

and the resulting system of equations is solved by the "stepping" technique. The results are in the form of frequency response plots (i.e., Bode Plots), from which feedback controllers can be designed.

The experimental technique consists of perturbing a distillation column and recording the outputs as a function of time. Many inputs can be used but a pulse input has many advantages over the others. The presentation in V-B describes how the output data to a pulse input can be analyzed so as to obtain frequency response diagrams.

Both of these methods are based on linear (ized) models, and hence the controllers will be satisfactory in the vicinity of the steady-state operating conditions. It is best to test these controllers on a more rigorous nonlinear model of the column developed in Part IV.

Part VI is devoted to the control of both product compositions and to the problem of interaction. A simple and useful measure of interaction in multivariable control problems is Bristol's Interaction Matrix. This interaction measure is developed and applied to some simple problems in VI-A. Its application to distillation (Part VI-B), assists in the selection of proper pairing of manipulated and controlled variables. This is followed, in Part VI-C, by the design of decouplers for achieving noninteracting feedback control of distillation columns. The design leads to Bode plots from which the transfer functions of decouplers can be approximated for implementation on hardware. This procedure is also based on a linearized model of the process, and the validity of these decouplers should be tested on a nonlinear model of the column developed earlier.

Part VII is concerned with advanced control schemes for distillation columns. Part VII-A discusses the advantages of feedforward control over feedback control. This is followed by the design of feedforward controllers. The gain terms of the feedforward controllers can be obtained from the material balance. In order to include dynamics, analysis of Part V-A (or experimental data), are needed. This analysis leads to Bode plots from which feedforward controller transfer functions can be obtained. The benefits of combined feedback/feedforward over feedforward and feedback control schemes can be demonstrated through simulation.

Part VII-B discusses an advanced scheme in which inexpensive multiple measurements on a

column are used to estimate the product composition. The estimate is then used to manipulate appropriate streams to hold product quality constant. There is scope here also to validate the results through simulation.

Part VIII outlines some special problems in distillation operations. The first of these to be covered is the inverse response in columns. The column base liquid level, for example, may temporarily increase due to an increase in reboiler heat duty. Part VIII-A examined the transfer function of a process, and illustrates how a positive zero can give rise to inverse response. Next, the equations needed to predict inverse response in distillation columns are developed. These equations serve as an aid in checking the design of distillation columns for inverse response. The remedy may consist of an alternate design for new columns or a different control scheme for operating columns.

Part VIII-B discusses override control schemes and the need for them. Often, conventional control schemes are inadequate in the presence of large upsets. In such cases, the override control schemes alter the appropriate streams so as to maintain the column in the safe operating region (or even cause shutdown if warranted). The hardware needed to implement these schemes is also discussed here.

Part IX in this course considers instrumentation hardware. The elements for the measurement of flow, liquid level, pressure, temperature, and composition are covered. This is followed by controller mode selection for loops involving the above

The benefits of combined feedback/feedforward control schemes can be demonstrated through simulation.

variables. Finally, the characteristics and selection of control valves and the effect of characteristics on loop linearity is studied.

CONCLUDING REMARKS

IT IS BELIEVED that this course fills the gap between a conventional course on distillation and the dynamic operation of distillation towers. It can be taught as a complete course in distillation controls, or portions of it can be combined with a conventional course on distillation.

The course outline of Table I does not include optimal control and computer control of towers because these topics require an additional background in optimization and the z-transform methods (Perhaps these can be covered in individual courses in optimization and computer process control, respectively). □

ACKNOWLEDGMENT

The author thanks his colleague, Professor P. M. Christopher, for reviewing this manuscript.

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FUSION REACTOR TECHNOLOGY

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AS A CONSEQUENCE of growing interests of members of the Chemical Engineering Department at Princeton in research problems related to the development of thermonuclear fusion reactors, a program in fusion reactor technology was established in 1972 in the School of Engineering and Applied Science. This program provides a coordination of study and research at all degree levels for students interested in the engineering and technological aspects of controlled thermonuclear research. Readers interested in why a program in fusion reactor technology should be born in a ChE department are referred to the lively article by Axtmann [1] describing the contributions of chemical engineers to nuclear engineering.

The idea of controlling the fusion reactions of the hydrogen bomb for the generation of electric power originated in the then classified work of Project Matterhorn at Princeton and resulted in the first conceptual design of a fusion power reactor, the so-called Model D Stellarator report of Spitzer et al. [2]. Given the level of knowledge of the time, that report was singularly prescient in identifying the major scientific and technological problems that would have to be solved to achieve a practicable power generator. The problems of plasma physics were clearly of paramount importance, and as a consequence, a major theoretical and experimental program in plasma physics has developed at the Princeton Plasma Laboratory, the largest American enterprise devoted to controlled thermonuclear research and the only large one on a university campus.

Members of the ChE faculty have long been associated with the Plasma Physics Laboratory (two for more than twenty years) and involved in researches on various technological problems related to fusion power development. However, there had been little incentive to formalize a pro-

gram in fusion reactor technology until recently when it became clear that the plasma physics problems were likely to be solvable and that the world energy situation would make fusion an increasingly attractive alternative source of energy.

COLLABORATION WITH PLASMA PHYSICS

THE PROGRAM IN fusion reactor technology was established in collaboration with the Plasma Physics Laboratory. There are six regularly enrolled graduate students in it plus about an equal number of undergraduates. Two full-time faculty and two part-time faculty are active in the program, and two other faculty members have related research interest. In addition there are, from time to time, visiting scholars from abroad.

Three courses involving fusion reactor technology are offered each year at Princeton. All three are taught in the Department of Chemical Engineering. Two are senior level undergraduate

Dr. Ernest F. Johnston is Professor of Chemical Engineering at Princeton University and Associate Dean of the Faculty. He was awarded his B.S. degree from Lehigh University and was then associated with Allied Chemical and Dye Corporation as research engineer, project leader, and production control supervisor. For two years he was at the Thermodynamics Research Laboratory at the University of Pennsylvania where he received his Ph.D. He has contributed significant research to the area of study concerned with the automatic control of industrial processes, and he is the author of numerous papers in this field, including a chapter in **Advances in Chemical Engineering** and a book **Automatic Process Control** published by McGraw-Hill Book Co. (1967). He has published extensively in other aspects of chemical engineering including molecular transport properties, thermodynamics and fusion technology. Since 1955 he has been associated with the Plasmas Physics Laboratory on Princeton's James Forrestal Campus where he is concerned with the technological problems of thermonuclear fusion power reactors. He adds "I am an amateur boat builder, Milton scholar, and musician (voice, piano and pipe organ), and I practice gentleman farming at our summer home on the Maine coast. I commute to work by bicycle, risking knock-off by motor vehicle to avoid knock-off by heart attack."

courses, Ch.E. 417 and 418, Nuclear Engineering I and II, and the third is Ch.E. 550, Fusion Technology, the graduate course described here. The first of the undergraduate courses is concerned primarily with fission processes, and fusion topics are introduced only briefly. The second undergraduate course, however, deals solely with fusion problems, emphasizing plasma behavior, the engineering aspects of plasma research, magnet design, and similar subjects. It provides a background useful for the graduate course.

Both undergraduate courses may be elected by graduate students and by properly qualified juniors and seniors. These courses are populated by students from a variety of engineering and science disciplines.

The graduate course was designed primarily for first-year graduate students in the fusion reactor technology program but a number of other students elect it as well. A principal objective is to provide an up-to-date perspective on the major problems and current researches in the technological aspects of fusion power development. The catalog description is:

Ch. E. 550. Fusion Reactor Technology

A study of contemporary problems in the development of nuclear fusion reactor systems. Plasma problems, fuel cycles, materials, blanket problems, energy extraction and power cycles, non-power uses of energy output, reactor control, environmental problems. Prerequisite: ChE 418 or equivalent.

Three faculty members share equally in the formal instruction in the course. They are Robert C. Axtmann, Professor of ChE for Environmental Studies, Ernest F. Johnson, Professor of ChE and Robert G. Mills, Head of the Fusion Reactor Design Division of the Plasma Physics Laboratory and Lecturer in ChE with rank of Professor. Approximately three-quarters of the class time is used for their lectures. The remaining quarter comprises seminars by students in the course and by other faculty members on selected topics in the field. Because of the disparateness of many of the topics the lecturers frequently alternate, and the seminars are scattered throughout the term albeit somewhat more heavily concentrated toward the end of the term.

There is no single textbook suited to this new field. Because of our historical and continuing link to the Plasma Physics Laboratory the principal focus of the treatment is on magnetically confined plasma machines rather than laser driven devices, and we tend to use as a major reference

the conceptual design report edited by Mills [3] and published by the Plasma Physics Laboratory. This nearly 600-page report is the most detailed design study for a fusion power reactor currently available. This volume, with its numerous references, constitutes a comprehensive introduction to the field. The design is based on a minimal employment of new technology. In particular,

The idea of controlling the fusion reactions of the hydrogen bomb for the generation of electric power originated in the then classified work of Project Matterhorn at Princeton and resulted in the first conceptual design of a fusion power reactor.

materials of construction involve only those for which there is a proved fabrication capability. Even so, there are many uncertainties in the design since there are large areas of ignorance. These uncertainties are discussed at some length in the report, and hence they provide a good springboard for examining the major problems in fusion power development.

Four copies of the Mills design report together with one each of the reference books listed below are placed on reserve in the Engineering Library for use by students during the course.

RESERVE LIST

1. "A Short Course in Fusion Power," NP-20040, USAEC, NTIS, 1972.
2. Chen, Francis F., "Introduction to Plasma Physics," Plenum Press, New York, 1974.
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4. Gruen, D. M., editor, "The Chemistry of Fusion Technology," Plenum Press, New York, 1972.
5. Kammash, T., "Fusion Reactor Physics Principles and Technology," Ann Arbor Science Publications, Inc., Ann Arbor, Michigan, 1975.
6. Mills, R. G., editor, "A Fusion Power Plant," MATT 1050 Princeton Plasma Physics Laboratory, Princeton, New Jersey, 1974 (available through NTIS, U. S. Department of Commerce, Springfield, Virginia 22151).
7. Rose, D. J., and M. L. Clark, "Plasmas and Controlled Fusion," MIT Press, Cambridge, Massachusetts, 1961.

In addition to the reserved books there are

strong collections of publications on fusion technology maintained by the Engineering Library and also by a satellite library at the Plasma Physics Laboratory on the Forrestal Campus. Many of these publications are in the form of proceedings of international symposia and workshops on specialized aspects of fusion technology sponsored by various agencies like Energy Research and Development Administration (ERDA) and technical societies like the American Nuclear Society and the Institute of Electrical and Electronics Engineers (IEEE).

The graduate course was designed primarily for first-year graduate students in the fusion reactor technology program but a number of other students elect it as well. A principal objective is to provide an up-to-date perspective on the major problems and current researches in the technological aspects of fusion power development.

Because of the rapid growth of knowledge in many aspects of fusion technology and shifting emphases as new constraints arise and old ones change, the content of the course will vary from year to year. Last fall the formal coverage included a brief overview of the world energy problem to show what contributions might be expected of fusion power, a detailed review of the Princeton Reference Design to identify the major problems and some possible solutions, a treatment of the problems of plasma physics as a basis for setting the scale of realistic machines and fixing many of their properties, and an examination of the environmental problems arising from power plants generally and from fusion power plants in particular.

Although some problems had to be treated cursorily, either for lack of time or because current understanding is uncertain, every major problem was addressed in the formal part of the course. Some like the use of molten salts as tritium breeding media the permeation of hydrogen isotopes in metals were addressed in greater detail because of the special interests of particular faculty members.

During the term eight seminars were conducted in the course on the following subjects:

1. Low Concentration Permeation
2. Ion Bombardment of Metals
3. Fission-Fusion Hybrids

4. Parametric Systems Analysis
5. Laser Fusion
6. Alternate Fuel Cycles
7. Non-Power Uses of Fusion
8. Fuel Injection

Concurrently with the graduate course in fusion reactor technology a series of ten seminars on vacuum technology and engineering was offered by a physicist from the Plasma Physics Laboratory as part of the program in fusion reactor technology. A similar seminar series on neutronics was offered during the preceding term. As a consequence neither of these topics was discussed in any detail in the graduate course.

Although we have offered the course only once, our assessment, arrived at in consultation with our students, is that we have fairly met our objectives. We anticipate that we will follow essentially the same format when we offer the course again this fall. In contrast with the first offering we shall probably include some homework problems and examinations to provide a better feedback on our teaching. □

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Continued from page 167.

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ENVIRONMENTAL COURSES

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DURING THE PAST THREE years at the University of Pittsburgh the Chemical Engineering Department has developed two courses dealing with the environment for advanced undergraduates and graduate students. One is entitled, "Atmospheric Pollution" and the other, "Industrial Waste Treatment." These courses developed from joint student-faculty-industry interest and cooperation. Not only have chemical engineering students participated in the program, but other science and engineering students have also taken these courses.

The University's location in a heavily industrialized city has been a particular advantage for the study of the environment in these courses. Cooperation with industrial and government organizations has given the courses a unique quality of seeing and being involved in the most immediate and relevant problems of an industrial city.

In the atmospheric pollution course, the Pittsburgh problem was stressed and used as a basis for analysis. The sulfur dioxide and suspended particulate matter problems were presented more than the nitrogen oxides or any other pollutant problems. The course ran 15 weeks, which is one trimester having three hours of class time per week. This course was held on one evening in

The final part of the course looked at equipment, design and economics. Process treatments, scrubbers, bag houses, cyclones, electrostatic precipitators, etc., were handled. The cost of these units as well as a treatment of cost-benefit analysis of air pollution control in general was presented.



George Klinzing received his BS degree in Chemical Engineering from the University of Pittsburgh and his MS and PhD from Carnegie-Mellon University. He spent three years teaching and consulting in chemical engineering at Central University in Quito, Ecuador. His interests are transport phenomena and engineering education in and technology transfer to developing countries.

order to accommodate the large number of part-time graduate students from the industrial community of the area.

The first week was devoted to an introduction to air pollution both on a global and local basis. Definition of terms and identification of sources were detailed. Chapters 1-5 of McCormac [1] and Chapter 1 of Strauss [2] were required readings. The next two weeks were dedicated to atmospheric transport by dispersion models. Comparison between models and evaluation of coefficients of dispersion were treated. The effects of inversions, chemical reactions and finite absorption of the pollutants at ground level was studied in the modeling. The many plume rise equation were viewed and controversy aired on the various analyses. The book by Ledbetter [3] was also used as reference material.

Sampling and analysis were next scrutinized. The EPA sampling train and other EPA regulations on sampling were covered. At this point, an industrial representative from a local power com-

pany discussed the practical aspects of sampling commenting heavily on the regulations specified by EPA in the Federal Register. Considerable class interaction took place at this point and an appreciation of the industrial problem was realized. These topics took two weeks to study.

LEGAL ASPECT

THE LEGAL ASPECTS of air pollution are indeed complex. Some of the more famous cases were viewed and the pending legal situation of cases in Allegheny County (Pittsburgh being the County Seat) were discussed. A representation of the State of Pennsylvania's Department of Environmental Resources gave a lecture discussing some specific cases and showing the legal process that needs to be followed in prosecuting a violator. Routine inspections and testing were explained and problem areas mentioned as to enforcement of the law. Two weeks were spent in total on the legal topic.

The next three to four weeks were spent on sulfur dioxide and suspended particulate matter analysis. Detection techniques, sources and abatement procedures were treated. Chapters 3-10 of Strauss were utilized as a basis with government publication assisting in the treatment. [4] The various types of equipment for analysis and sampling were brought into class when possible, and the advantages and disadvantages of the units explained in detail.

The final part of the course looked at equipment, design and economics. Process treatments, scrubbers, bag houses, cyclones, electrostatic precipitators, etc. were handled. The cost of these units as well as a treatment of cost-benefit analysis of air pollution control in general was presented.

In addition to quizzes and a final exam, the students in groups of 2 or 3 worked on a project during the term related to the air pollution area. Some topics were suggested and others were originated by the students. Some of the topics for analyses were:

- CO Concentrations in Oakland (University Area)
- Pressure Swing Adsorption Cycle on Auto Emissions
- Infra-Red, Gas Chromatographic Analysis of Pollutants
- Indoor Level of Pollutants (Engineering Hall, Student Dormitories)
- Multiple Stack Analysis

- Plume Rise Calculations (Comparison and Analysis)
- Flow Patterns Around Buildings

WASTE TREATMENT COURSE

THE SECOND COURSE in the environmental area was "Industrial Waste Treatment." This course met for the same length of time and same time slot as the "Atmospheric Pollution" course. The base text for the course was Nemerow. [5] The first four to five weeks of the course were dedicated to understanding the basics of industrial waste treatment and roughly Chapter 1-20 in Nemerow were covered. Here again, definitions are essential such as BOD, COD, and TOD. The basic operation of neutralization, sedimentation flotation, activated sludge, and trickle filters were handled showing the basis for analyses from mass and heat transfer approaches. Detailed designs of a base case for each one of these units were presented. [6] This preface was used as a basis

One course is entitled, "Atmospheric Pollution" and the other, "Industrial Waste Treatment." These courses developed from joint student-faculty-industry interest and cooperation.

for industrial representatives to present lectures on specific industrial waste problems concerning mostly the Pittsburgh area. To begin the special lectures a professor of Environmental Law talked in general and specific on industrial waste problems stressing changes in legal interpretation and sentiment. A consultant in the Pittsburgh area spoke on wastes in the tanning industry showing that as the laws are presently written and considering the small size of such tanning operations the industry would probably die in the United States in the next few years.

Wastes in the food industry was given by an engineer from the H. J. Heinz Co. and another consultant in the environmental area spoke on waste water parameters and measurement for treatment control. Both speakers stressed high costs with the Heinz representative giving detailed information on financing of an industrial waste treatment. The pitfalls of waste water measurement were mentioned by the consultant showing you can rely very little on most measurement in the waste water analysis field including the

standard pH measurement.

Radioactive waste disposal was handled by Westinghouse and a representative of United States Steel Corporation gave an excellent treatment of the steel industries problems and programs. The municipal waste and their ability and willingness to handle industrial discharge was presented by the county's municipal disposal facility, ALCOSAN. Jones and Laughlin Steel Corporation presented the coal mining waste problem and treatment. Effective treatment can be inacted on new mines; but old abandoned ones are the areas most difficult to clean-up.

THERMAL POLLUTION

DURING THE LAST WEEK of the course, the thermal pollution area was treated with consideration from power plants both coal fired and atomic. Much of the atomic power plant material tied in with the radioactive waste treatment lecture.

BOOK REVIEW: Multivariable Computer Control

Continued from page 154

publish these together in a single volume. The result is the present book.

The authors have been able to present a coherent view of their work by appending introductory discussion to previously published papers and organizing this by topic. It may be useful to summarize briefly the scope of the material. Section 1 presents an overall view of the book, while Section 2 treats several different approaches to modelling the process. Of particular interest is a comparison of model reduction procedures and a study of several approximate low order models of the process. Section 3 demonstrates the dynamic performance to be expected under conventional control while Sections 4-6 discuss more modern computer control techniques. These sections present a detailed comparative study of techniques such as a multivariable feedback control, combined feedforward-feedback control, time optimal control, optimal linear-quadratic feedback control, model reference adaptive control, etc. Section 7 presents experimental testing of on-line state estimation (using Kalman Filters) and the incorporation of the state estimator into a stochastic feedback control scheme. Finally Section 8 describes the overall educational aspects of such computer control facilities.

In short, reliance on industry for up-to-date information and a special viewpoint was very successful both in the atmospheric and industrial wastes courses offered. Our area indeed is rich in capable, knowledgeable engineers willing to assist in the preparation of meaningful courses on the environment for the students of our engineering schools. □

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The case study would be of interest to anyone wanting to evaluate the experimental performance of a number of modern process control techniques. However, as one who has used this case study (in manuscript form) with good results in a graduate process control course, this writer feels the greatest value of the book is as a supplementary text in such a graduate course. The availability of a single process from which to draw experimental examples of model linearization, model reduction, single loop feedback control, multivariable feedback control, multivariable optimal feedback control, state estimation, etc., allows the student to study a new method on an already familiar process and to compare with methods already discussed. As a supplement to lectures over the fundamental mathematical methods, we found the case study extraordinarily helpful.

BOOK RECEIVED

Organic Electronic Spectral Data. Vol. II, 1969.

Edited by J. P. Phillips, H. Feuer, P. M. Laughton and B. S. Thyagarajan.

John Wiley & Sons, Inc. New York, 1975.

1075 pages.

This is volume II in a continuing compilation of ultraviolet-visible spectra of organic compounds presented in the journal literature.



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ADSORPTIVE BUBBLE SEPARATION METHODS

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TO MOST ENGINEERS, the adsorptive bubble separation methods [1,2] are a largely unfamiliar group of techniques. This may be due in part to the fact that these techniques are intimately based on surface phenomena. Most engineers seem to be more comfortable when dealing with bulk phenomena than with surface phenomena. Such a preference can prove awkward when an investigator or designer is faced with certain classes of problems.

The adsorptive bubble separation methods involve selective adsorption or attachment at the surfaces of bubbles rising through a solution or suspension. If the material to be adsorbed or attached, which is termed the colligend, is not surface active, a suitable substance called a collector may be added to unit with the colligend to form a surface active sublance which is carried up by the bubbles.

Prominent among these techniques, either in terms of application or research interest, are the flotation of particulate matter in wastewater treatment and in mineral beneficiation [ore flotation] [3], the foam fractionation of dissolved or fine colloidal matter [4], the collector-required technique of ion flotation [5], the precipitate-required technique of precipitate flotation [6], the foamless technique of bubble fractionation [7] which capitalizes on the vertical concentration gradient that is established in a vertically-elongated bubbled pool of liquid, and the foamless technique of solvent sublation [5] which makes use of an immiscible auxiliary liquid atop the main pool to entrap the adsorbed material from the existing bubbles. For the sake of brevity, the term adsorptive bubble separation methods is sometimes contracted to adsubble methods [1,8].

In order to acquaint interested graduate

students with this somewhat unusual group of separation techniques, some years ago the writer established an elective graduate lecture course on the subject. It runs for an academic quarter and is offered in approximately alternate years. It was originally offered for only 2 credits, but it recently has been expanded to 3 credits and has been opened to qualified seniors as well as to graduate students.

The text for the course is "Adsorptive Bubble Separation Techniques" by Lemlich [9]. Emphasis is placed on the first eight chapters which constitute half the book. Supplementary material, which includes some solved illustrative problems [10,11], is drawn from other sources. Table 1 presents an abbreviated outline of the course.

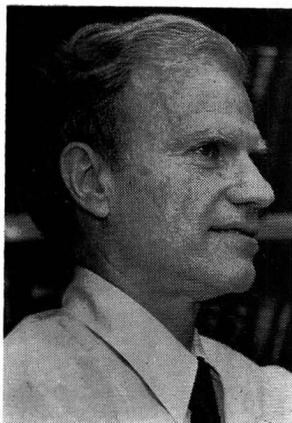
The course begins with an introductory overview of the field. The various adsubble techniques are briefly described and compared. The pervading importance of surface activity and solute surface excess are carefully noted.

SURFACES AND BUBBLES

NEXT, SURFACE TENSION is discussed and the common methods for measuring it are reviewed [12]. The equation of Laplace and Young for the pressure difference across a curved interface is derived, and the result is applied to the submerged bubble, the free bubble, and the Plateau border. For reinforcement of learning, these three special cases are also derived directly from fundamental force balances.

TABLE 1
Abbreviated Outline of Course

1. Introduction
2. Surfaces and bubbles
3. Foam
4. Adsorption
5. Foam fractionation
6. Flotation
7. Foamless separations
8. Student presentations



Robert Lemlich received his B.Ch.E. summa cum laude from New York University, his M.Ch.E. from the Polytechnic Institute of Brooklyn, and his Ph.D. from the University of Cincinnati (1954) where he is presently Professor of Chemical Engineering. He has also held Fulbright lectureships to Israel (1958-59) and Argentina (1966). He is a Registered Professional Engineer, a Fellow of the American Association for the Advancement of Science, and is listed in *Who's Who in America*. His research interests are in bubbles, foam, and heat transfer.

The generation of bubbles is described. Empirical [13] and theoretical [14,15] unimodal frequency-distribution functions are discussed, as well as pathological [bimodal] distributions [16]. Mean bubble radii based on various combinations of moments are introduced. The propriety of $r_{3,2}$ for adsorption and $r_{3,1}$ for drainage is derived.

The general morphology and characteristics of foam are presented [17,18]. Foam stability is explained in terms of the liquid and surface viscosities, the Gibbs and Marangoni effects, and, for ionic surfactants, the electrostatic repulsion across the film. The two general mechanisms of foam instability are delineated, namely film rupture [19] and interbubble gas diffusion [13]. Theory for the latter mechanism [13] as well as for foam drainage [16,20-22] is covered in some detail.

Various methods for measuring pertinent properties of and in foam are presented. These include surface viscosity by movement within films [23], film thickness by diffraction of light [23], and liquid content of foam by total collapse or by electrical conductivity in situ [24,25]. Bubble sizes are usually measured photographically. Accordingly, derivations are presented in detail for the correction to the frequency size distribution for planar statistical bias [13] and its step effect [26] on any mean radius [true $r_{j,k}$ = planar $r_{j-1,k-1}$].

The general Gibbs adsorption equation [27] is detailed and several important special cases are

discussed. For the sake of clarity and reinforcement, the simple case of a pure dilute solution of a simple nonionic surfactant is also derived directly [28].

The Langmuir isotherm [29] is derived and its important limiting cases are noted. The effects of insufficient collector, excess collector, micelles, and competing ions are considered. Selectivity is discussed.

SEPARATION METHODS

THE SIMPLE, STRIPPING, enriching, and combined modes of operation are presented in detail. The important concept of effective concentration in the upflow is introduced. Transfer units and theoretical stages are discussed and methods for their calculation are derived [10,30,31].

For utility as well as learning reinforcement, the limiting equations for separation in tall counterflow columns are derived from transfer units, theoretical stages, and also directly from fundamentals. The effect of internal reflux induced by coalescence in the rising foam is discussed [30].

The physical and chemical parameters affecting ion flotation are covered. The selectivity, thermodynamics, and kinetics of the separation are discussed.

**The adsorptive bubble
separation methods involve
selective adsorption or attachment
at the surface of bubbles rising through
a solution or suspension.**

Precipitate flotation of the first kind, in which a separate surface-active collector is added to coat and thus float the precipitate, is distinguished from precipitate flotation of the second kind in which no separate collector is required. The effects of the various parameters are discussed and precipitate flotation is compared with ion flotation.

The elements of mineral flotation are presented. Some of the technology [32] is also surveyed. However, since mineral flotation belongs more properly in the field of mining engineering and extractive metallurgy, it is not covered in detail in this course which is intended primarily for students in chemical engineering.

The lumped parametric approach to analyzing

batchwise bubble fractionation is presented [33], and results are compared with experiment [34]. The theory is extended to continuous flow and also compared with the distributed parametric approach [35].

Solvent sublation is introduced and compared with bubble fractionation. It is also compared with conventional liquid extraction. The immiscible layer of solvent sublation can trap more than can the layer in liquid extraction which is limited by considerations of bulk equilibrium.

PRESENTATIONS AND DEMONSTRATIONS

SOME OF THE MANY systems separated by the adsubble techniques are surveyed throughout the course. Each student is then required to write a term paper and in some cases present a brief oral report on some group or aspect of these separations. Appropriate supplementary literature is provided.

Some typical topics are as follows: a) Applications to sewage treatment; b) Phenol removal; c) Natural adsubble phenomena in the sea and the

**For the sake of brevity,
the term adsorptive bubble
separation methods is sometimes
contracted to adsubble methods.**

effect on the marine aerosol; d) The adsorptive droplet separation methods (which are the liquid-liquid analogs of the adsorptive bubble separation methods).

It has been the author's experience that the inclusion of an occasional, simple, inexpensive but well-chosen brief demonstration can add spice to a lecture course while at the same time illustrate principles in a convincing manner and thus enhance the learning process [36,37]. Some examples for this course include the following: (a) A razor blade floated by surface tension and dramatically pushed aside by a single tiny droplet of surfactant but scarcely moved by a second droplet; (b) The foam fractionation of dilute crystal violet chloride from scarlet red in the presence of sodium sulfate and the collector sodium lauryl sulfate by simple shaking (and the failure to visibly separate in the presence of too much collector); (c) The bubble fractionation of dilute crystal violet chloride in the presence of sodium sulfate in a

tall narrow vertical glass tube by bubbling with air or nitrogen; and (d) the simple Crits ring test for the presence of trace surfactants in water [38] that has been shown to function by virtue of transient adsubble separation [39].

CONCLUDING REMARKS

BY THE END of this course the student has become familiar not only with the adsubble techniques but also with some of the important universal concepts of surface phenomena. He has also learned some ways in which they can be applied. He is thus better equipped to deal with a class of problems that might otherwise cause him great difficulty during his subsequent professional career. □

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Continued on page 186.

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INTRODUCTORY POLYMER SCIENCE AND TECHNOLOGY

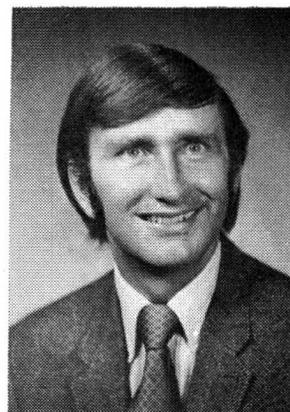
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IN THE COURSE OF THIRTY years the polymer industry has grown enormously to the present levels of production comparable to that of steel. It is estimated that 30% of all chemistry and ChE graduates are employed in some field of endeavor involving polymeric materials. In this time period the industry matured and many scientific and engineering principles of polymerization, polymer processing and polymer fabrication have been well established. A general course and laboratory experience in polymers certainly will be an important aspect of ChE education for years to come.

Today the maturing and importance of the polymer field have resulted in many new courses being adapted in well established programs as well as the proliferation of basic courses in polymers for many departments which, up until recently, have not had a course in polymer science and technology. The first level foundation course is of great importance since it should acquaint students with the basic subject material, reveal the breadth of the polymer field, and yet challenge the gifted student. Wisconsin has had such a course for many years which has been continually updated. An interesting development, particularly in the past five years, is the variety of backgrounds of students taking such a course. Students representing chemistry, metallurgy, physics, materials science, engineering mechanics, mechanical, electrical as well as chemical engineering, have elected to take this course. The course is aimed mainly for senior and graduate ChE level students, although interested junior level students, who have had thermodynamics, physical chemistry and organic chemistry are also encouraged to take the course. Graduate students from other

departments who have not had basic prerequisites in two of the three aforementioned areas are generally discouraged from taking the course. The course has been very well received and enrollments have been large, averaging about 35 students each semester.

The course is developed to achieve a balance of many of the disciplines of polymer science and technology. This necessitates, a survey approach. However, homework problems are specific enough for the student to obtain a deeper insight into many of the topics covered in lecture. In a sense, the course is designed to "whet the appetite" as well as feed specific information about the polymer field. Classroom demonstrations of polymer properties have been of particular educational value and are listed as follows: solution, mechanical (modulus, elasticity, shrinkage on annealing, time effects and fracture), optical (birefringence, scattering, and spherulitic structure), wettability and flammability. Also the



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examination of various commercial forms of typical plastic materials has been quite enlightening to the students. For instance, the film, fiber and molded articles made from polyethylene, polyethylene terephthalate and the polyamides reveal the enormous flexibility of property design via polymer processing methods.

The course outline is as follows:

TABLE I. Course Outline

	APPROXIMATE NO. OF LECTURES
I. INTRODUCTION	1
A. Basic Definitions	
B. Unique Properties of Polymers	
C. Cohesive Energy Density and Properties	
II. POLYMERIZATION	
A. Condensation	3
B. Addition	3
C. Copolymerization	1
D. Polymer Reactions	1
III. STRUCTURE AND PROPERTIES OF POLYMERS	
A. Measurement of Molecular Weight and Size	3
B. Polymer Solutions	2
C. Analysis of Polymers	2
D. Testing of Polymers	2
E. Morphology and Order in Crystalline and Amorphous Polymers (Processing Effects)	2
F. Polymer Structure and Mechanical Properties	2
G. Polymer Structure and Diffusion Properties	1
H. Polymer Structure and Optical Properties	1
I. Polymer Structure and Electrical Properties	1
IV. PROPERTIES OF COMMERCIAL POLYMERS	
A. Olefin Polymers	2
B. Diene Polymers	2
C. Vinyl and Vinylidene Polymers and Copolymers	2
D. Heterochain Polymers (Polyamides, Polyesters, Polyimides, Polyethers)	3
E. Cellulosic Polymers	1
F. Thermosets	2
V. POLYMER PROCESSING	
A. Resin and Plastics Technology (Molding, Extrusion, Compounding, Calendering, Casting)	4
B. Fiber Technology (Melt and Solution Spinning, Annealing, Dyeing)	1
C. Elastomer Technology (Compounding, Vulcanization, Molding)	2
	44

Any required background text for such a course usually has certain limitations. Therefore additional supplementary material introduced in the lectures is necessary to expand the concepts found in the required text. Even though this requires additional work in terms of pedagogy the rewards are great since one can "flavor" the course with different approaches. Presently the

An excellent complementary course for students is a basic laboratory experience which includes experiments on polymerization, polymer fabrication and polymer properties.

required text is F. W. Billmeyer's, *Textbook on Polymer Science*, 2nd edition, Interscience publishers (1971). Additional texts, which have been used for supplementary information include the following:

Polymerization

Organic Chemistry of Synthetic High Polymers, R. Lenz, Interscience (1967).

Polymer Chemistry, B. Vollmert, translated by E. H. Immergut, Springer-Verlag (1973).

Polymer Science and Engineering, D. J. Williams, Prentice-Hall, (1971).

Structure and Properties of Polymers

Engineering Design for Plastics, ed. E. Baer, Reinhold (1964).

Viscoelastic Properties of Polymers, J. Ferry, John Wiley (1970).

Principles of Polymer Chemistry, P. J. Flory, Cornell University Press (1953).

Modern Plastics Encyclopedia, ed. S. Gross, McGraw-Hill.

Polymer Processing

Plastics Processing, J. M. McKelvey, John Wiley (1962).

Rubber Technology, M. Morton, Reinhold (1973).

Plastics Film Technology, W. R. R. Park, Reinhold (1969).

As one can see from the outline and references, the course is broadly based and includes a great deal of information. For handling the supplementary lecture material not covered in the required text, extensive handouts are given to the students to facilitate questions in class and allow more specific homework problems to be assigned.

LABORATORY EXPERIENCE

AN EXCELLENT COMPLEMENTARY course for students is a basic laboratory experience which includes experiments on polymerization, polymer fabrication and polymer properties. The following is an outline of a course which is

offered on a yearly basis and has enrollments of 12 to 15 students of which 30% have been of graduate standing. Larger enrollments have been handled by giving the laboratory twice a year. This approach has allowed for more individualized instruction which is quite necessary in a laboratory of this type since the equipment is generally expensive and chemicals are somewhat toxic.

The course is developed to achieve a balance of many of the disciplines of polymer science and technology. This necessitates a survey approach. However, homework problems are specific enough for the student to obtain a deeper insight into many of the topics covered in the lecture.

The course is divided into three one credit sections for flexibility. A list of the required experiments is given in Table 2.

TABLE 2. Laboratory Experiments

- I. POLYMERIZATION (1 credit)
 1. Suspension Polymerization of Polystyrene
 2. Preparation of Phenol-Formaldehyde and Phenol-Resorcinol Resins
 3. Preparation of Polyurethane Foams
 4. Kinetics of Polyesterification
 5. Preparation of Polysiloxane Elastomer
- II. CHARACTERIZATION (1 credit)
 1. Infrared Analysis of Polymers
 2. Fractionation of Polystyrene and Molecular Weight Measurements by Solution Viscosity
 3. Flammability of Polymers
 4. Differential Scanning Calorimetry of Polymers
 5. Nuclear Magnetic Characterization of Polymers
- III. FABRICATION AND TENSILE TESTING (1 credit)
 1. Molding of Phenolic Laminates and Composites
 2. Tensile Testing of Rigid, Thermoplastic, and Elastomeric Polymers
 3. Compression and Injection Molding of Thermoplastics and Thermosets
 4. Extrusion of Thermoplastics (Polypropylene)

The text used for the laboratory is, *Laboratory Preparation for Macromolecular Chemistry*, E. L. McCaffery, McGraw-Hill (1970).

Before the students can begin each experiment they must hand in a short report on the toxicity and carcinogenic properties of each chemical (including common solvents) which is used in the experiment. I might add this single requirement has produced desirable, positive effects on laboratory techniques. The students work in squads of

two or three since most of the experiments are elaborate enough to be difficult for one person either to control or set up. It normally takes three hours for completion of most of the experiments, however certain long experiments are split into two laboratory periods. The polymerization reactions which unfortunately cannot be split can take long times, especially the pearl polymerization of styrene. Some undaunted students have been known to stay ten hours to complete that experiment after two initial failures!

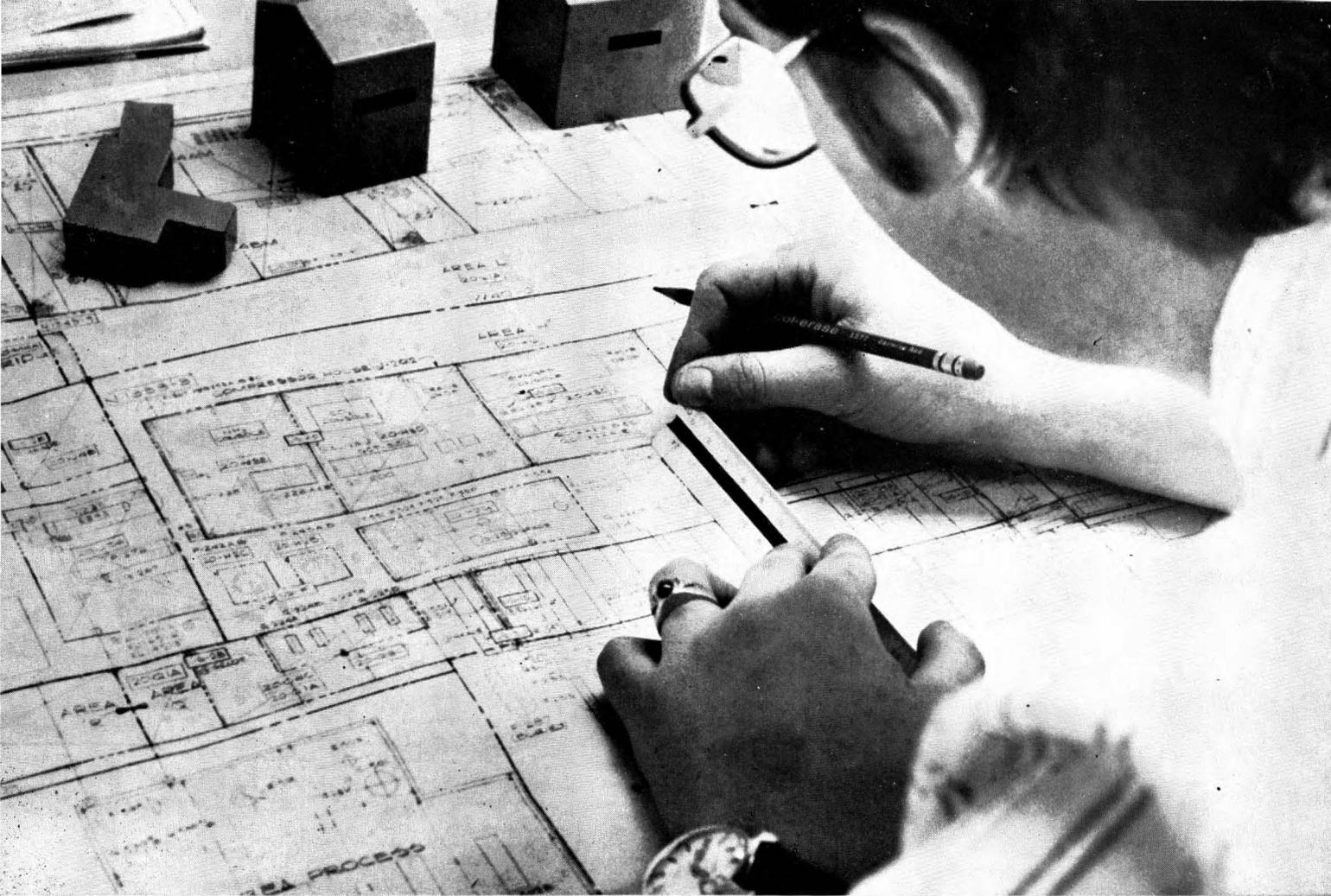
Additional experiments on light scattering, adhesion and fracture, and copolymerization have been designed and will be included in the following year.

These introductory courses have been useful for many graduate students embarking on higher level courses specific to polymers and particularly useful for the undergraduate ChE student who wishes a background of polymers to round out his academic career. Although the department does not yet require such a course for undergraduates, a large majority of our students avail themselves of the opportunity. □

LEMLICH: Adsubble Methods

Continued from page 182.

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THE ENGINEER AS AN ENTREPRENEUR - SOME NEW CONCEPTS

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NEW ENGLAND HAS NOT been blessed with a plethora of natural raw materials. At the same time its excellent university system, both in the private and public sectors, has produced a large quantity of engineers and scientists as well as skilled technicians. The result of these two factors has been the development of an economy based primarily on products with high technology input or of engineering and scientific services.

In order to maintain and improve its economic position, New England must continue its production of products and services requiring high technology. For continued growth, a continuing influx of new businesses must be maintained both to improve employment opportunities and to maintain or increase its tax base. Such a growth has been characteristic of the region in the decades of the 1950's and 1960's and a new upward thrust in this direction should be anticipated in the 1980's and beyond.

In an effort to aid in the development of better entrepreneurship in New England, the Chemical Engineering Department at Lowell Technological Institute has provided a new course called "*The Engineer as an Entrepreneur*." This course is open to seniors and graduate students, and is not restricted to chemical engineers. The course has been well received and has just completed its third year. The author has had considerable experience with entrepreneurial businesses in the area and is familiar with a number of such companies in New England.

The course has developed around the concept that the best way to learn to swim is to get in the water. A major part of the course is the establishment of small two- or three-man companies which develop a product, a marketing plan and a

financial plan to exploit the product. While engaged in the development of this new company, the students are exposed to lectures and discussions by entrepreneurs in the local area. They are also given lectures by patent attorneys, financial people, marketing people and government representatives. The implications of Chapter 11 of the Bankruptcy Laws are also discussed.

Unfortunately in a one-semester course it is impossible to try out the new product or service on the market in any but a very preliminary way. In most cases, prototypes of the product have been produced and local marketing evaluations have been made. Cash flow, financial requirements, and pro forma profit and loss statements have been produced for a five-year period.

At the end of the course, the full report of the company is presented to the entire class (with visitors) and the completed report is submitted as a fulfillment of the course requirements. The stipulation is that the report be written to be presented to a group of financial people to obtain their financial support for the project.

Textbooks dealing with the subject in all of its ramifications are difficult to find. Three books were used as references as follows:

1. *How to Run a Small Business*, J. K. Lasser (4th Ed., McGraw-Hill, 1974).
2. *Fun and Guts, the Entrepreneur Philosophy*, Joseph Mancuso (Addison-Wesley, 1973).
3. *The Small Chemical Enterprise and Forces Shaping the Future of the Chemical Industry*, (American Chemical Society, 165th Meeting, Dallas, Texas, April 10 through 12, 1973).

Other class handouts included publications by the Small Business Administration (SBA), the Department of Commerce of the Commonwealth of Massachusetts, and various U. S. Government publications.

Guest lecturers were brought into the class and included a patent attorney, a successful entrepreneur, a banker, and a financial advisor. A

field trip was made to a successful small company, Amicon Corporation, of Lexington, Massachusetts. A seminar was held with the president of the company, Norman D. Jacobs, who outlined the inception of the company and discussed many of the problems involved in the development and growth of Amicon. A plant visit was also scheduled subsequent to the seminar.

The students were given lectures involving the principles of business organization, problems of accounting, cash flow and depreciation, problems associated with markets and marketing and problems associated with production. Heavy emphasis was placed on both the marketing function and the financial function. Further emphasis was placed on the methods of incorporation of the corporation and various mechanisms for obtaining initial money to start up the company.

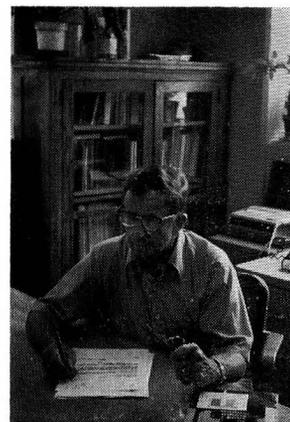
MARKETING RESEARCH

THE STUDENTS DID their own marketing survey usually on a local basis and discussed various problems associated with these marketing surveys with other members of the class.

The course has developed around the concept that the best way to learn to swim is to get in the water. A major part of the course is the establishment of two- or three-man companies which develop a product, a marketing plan and a financial plan to exploit the product.

Marketing research on a national basis was done in a preliminary way by literature evaluations and by direct contact with marketing organizations. Distribution systems, costs of selling and of operation and problems associated with capital investment were all discussed in detail.

The final reports were expected to reflect all of the problems which would normally be associated with the establishment of sound legal corporate structure, financial backing and projected profit and loss statements. Strong emphasis was placed upon the oft-neglected principle that Accounts Payable are due within 30 days, whereas Accounts Receivable may extend up to 120 days. This requires working capital to bridge the time gap. More small companies fail because of lack of understanding of this principle than any other single factor.



Howard H. Reynolds received his AB in Chemistry from Harvard University and his ScD in Chemical Engineering from M. I. T. He has worked in the Technical Dept. and Research Dept. of Wyandotte Chemicals Co. Subsequently he worked with the Davison Chemical Company, the Dewey & Almy Chemical Company, the Cryovac Company and was Vice-President of Research and Development for the Ludlow Corporation. Since 1963 he has been professor and chairman of the Chemical Engineering Dept. of Lowell Technological Institute. He has been a member of the following societies: ACS, AIChE, AAAS, SPE, TAPPI, New York Academy of Science and Sigma Xi. He was recently elected a Fellow of AIChE.

Three projects developed in this course are worthy of note. The first is a mechanical apple-picker, operated by one person, capable of a substantial increase in the harvesting of fruit with a marked reduction in bruising. A prototype machine was built and was exhibited to several potential customers who were very excited about the prospect. Preliminary cost studies indicated that labor savings would more than pay for the mechanical apple-picker in one season.

A second interesting product was a Tic-Tac-To game involving 625 holes for pegs. The game was designed primarily for the age group of 8 years to adults. A prototype was made and a local market survey received enthusiastic response. There is considerable interest in continuing this development if appropriate capital can be acquired.

A third product was the development of a 10-size signal generator for use in testing of electronic circuits with specific reference to radios and television sets. The product could be equipped with multi-purpose replaceable heads to expand the range of utility. Preliminary market surveys indicated that a substantial market did in fact exist and one of the members of the student company intends to carry forward the

Continued on page 194.

ENERGY, MASS AND MOMENTUM TRANSPORT -

The Treatment Of Jump Conditions At Phase Boundaries And Fluid-dynamic Discontinuities

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THE ABILITY TO DEAL quantitatively with *transport* phenomena accompanying phase and chemical transformations is the hallmark of the chemical engineer. But since the essentials of transport phenomena are, accordingly, a central

... the principal need in the future will be for creative engineers able to formulate and program the solution to challenging novel problems, not the now-routine problems which characterized (chemical) engineering earlier this century.

part of every ChE's *undergraduate* education, what then is the purpose of a *graduate* course in this subject? The answer lies in the fact that undergraduate courses tend to emphasize the solution of "classical" problems whereas, in practice, the solution to such problems has already been thoroughly computerized. The situation is what D. Gabor calls the "aristocratic revolution" within the engineering profession [1]—*viz.* the principal need in the future will be for creative engineers able to formulate and program the solution to challenging *novel* problems, not the now-routine problems which characterized (chemical) engineering earlier this century. This is our underlying premise at Yale and, in what follows, I illustrate how this influences my teaching of our graduate course in energy and mass transport. For definiteness, I have selected the treatment of "boundary conditions", one of the "Achilles' heels" of most undergraduate courses in transport phenomena.

COURSE CONTENT

THE PLACE OF OUR topic within the context of the one semester lecture course (EAS 254) is evident in Table 1. This course is not only taken by all graduate students in ChE but, each year, attracts students from other graduate majors at Yale (*eg.* Geology, Forestry, Materials Science, Fluid Physics, Physiology). As will become clear

TABLE 1
COURSE OUTLINE: Heat, Mass and
Momentum Transport Processes*

1. CONSERVATION PRINCIPLES
(Continuum Approach)
 - Fixed and moving macroscopic control volumes
 - Conservation relations in partial differential form
 - Jump conditions at phase boundaries, discontinuities
 2. PHENOMENOLOGICAL TRANSPORT LAWS AND COEFFICIENTS
 - Linear flux-driving force laws
 - Molecular level approach to transport coefficients
 - Actual and effective transport coefficients; turbulent transport
 - Similitude methods, implications
 3. ENERGY AND MASS TRANSPORT IN QUIESCENT MEDIA
 - Steady state conduction, diffusion
 - Transient conduction/diffusion; analytical methods
 - Numerical methods; finite differences, finite elements
 4. ENERGY AND MASS TRANSPORT IN MOVING MEDIA
 - Transport to/from submerged surfaces
 - Transport to/from duct surfaces
 - Transport in packed beds
 - Transport in jets, plumes, wakes; pollutant dispersion modeling
 5. SPECIAL TOPICS (as time permits)
 - Transport with simultaneous phase change
 - Transport with simultaneous chemical reaction
 - Low density flows (non-continuum effects)
 - High speed flows (viscous dissipation effects)
- *Textbook: Bird, R. B., Stewart, W. and Lightfoot, E. N., Transport Phenomena J. Wiley (1963) (Supplemented by papers from the current research/engineering literature)

via our example, this broad appeal follows from our emphasis on fundamental principles common to transport phenomena in these fields. Specific applications including numerical calculations, are covered mainly via graded homework sets (about 9) and 2 take-home open book examinations. Moreover, the course is not only intended for tomorrow's "computer modelers" of chemical processes—it has proved useful to students designing and interpreting experiments in chemical kinetics, both laboratory and pilot plant scale.

Our approach to the treatment of boundary conditions is not that they are a set of *ad hoc* prescriptions (usually stated without their underlying restrictions), but rather that they follow from the same conservation principles used to generate global conditions on chemical reactors or differential equations applicable within each region of the ChE's interest. This is shown in the "road map" (Fig. 1), which reveals that we formulate the conditions to be imposed at interfaces separating continua by applying "battle-tested" conservation (balance) principles (mass, energy, momentum, entropy) to a special type of semi-differential control volume (a "pillbox") straddling the moving interface. It is remarkable that while this approach is quite familiar to EE's studying electromagnetism, most ChE's have not been introduced to it.

LIMITATIONS OF THE USUAL APPROACH

UNDERGRADUATE ChE's typically feel comfortable imposing continuity of normal velocity, tangential velocity (no "slip"), tangential shear stress, normal pressure, temperature, heat flux and chemical potential across interfaces (usually phase boundaries, but here broadened to include fluid-dynamic discontinuities such as detonation waves in gases, or the interface between immiscible liquids). To illustrate the serious limitations of these "commonly encountered" prescriptions, consider the following student exercises:

**For definiteness,
I have selected the treatment
of "boundary conditions," one of the
"Achilles' heels" of most
undergraduate courses
in transport phenomena.**



Dr. Rosner's research interests include convective heat and mass transport, interfacial chemical reactions, phase transformations, combustion and aerosol phenomena, on which he has published over 90 papers. He received his Ph.D. in Aeronautical Engineering from Princeton University in 1961 following a bachelor's degree in Mechanical Engineering (*summa cum laude*) from City College of New York in 1955. Prior to joining the Yale faculty as an Associate Professor of Engineering and Applied Science in 1969, he headed a research group on interfacial chemical kinetics and transport at AeroChem Div. Sybron Corporation, Princeton, New Jersey. He has also been a Visiting Professor of Mechanical Engineering at Polytechnic Institute of Brooklyn-Graduate School, and a Visiting Scholar at Stanford University (Chem. Eng. 1968) and Imperial College—London (Mech. Eng. 1973). He is presently Professor of Chemical Engineering and Applied Science and Director of the High Temperature Chemical Reaction Engineering laboratory at Yale University.

- E1. It is often stated that at solid/fluid interfaces the fluid velocity equals the velocity of the surface itself (p. 37, BSL [2] and p. 94 WWW [3]). Moreover, Batchelor (Ref. [4], p. 68) states that "unless rupture occurs" at the interface between two contacting media, the normal component of fluid velocity must be continuous across the interface. Suppose, however, that a solid is subliming into the gas (eg. naphthalene in air). Would this above statement be true for the velocity components normal to the surface?
- E2. The shear stress is often considered to be negligible at gas/liquid interfaces (p. 37, BSL and p. 110 WWW). When wind drives a film of rainwater up your car windshield against the pull of gravity, would this assumption be justified?
- E3. For the energy equation one can frequently impose the condition of continuity of heat flux and temperature across an interface (p. 267, BSL). Would continuity of heat flux be valid if the interface were the site of a phase change?
- E4. A theoretician has argued that a conjectured fluid dynamic discontinuity is possible ("exists") since it is compatible with the laws of mass, momentum and energy conservation. Is his proof complete? Can a discontinuity exist if the specific entropy of the fluid decreases across the discontinuity (as in a solidification wave)?
- E5. For systems which need not be in mechanical, thermal or chemical equilibrium: a) would a discontinuity in tangential mass-averaged velocity, v_t ,

across an interface (eg. phase boundary) violate any basic conservation principle? b) Would a discontinuity in temperature, T , across an interface (eg. a shock wave) violate any conservation principle? c) Would a discontinuity in chemical potential across an interface (eg. a phase boundary) violate any conservation principle? d) What kind of restrictions do the conservation equations impose in such cases?

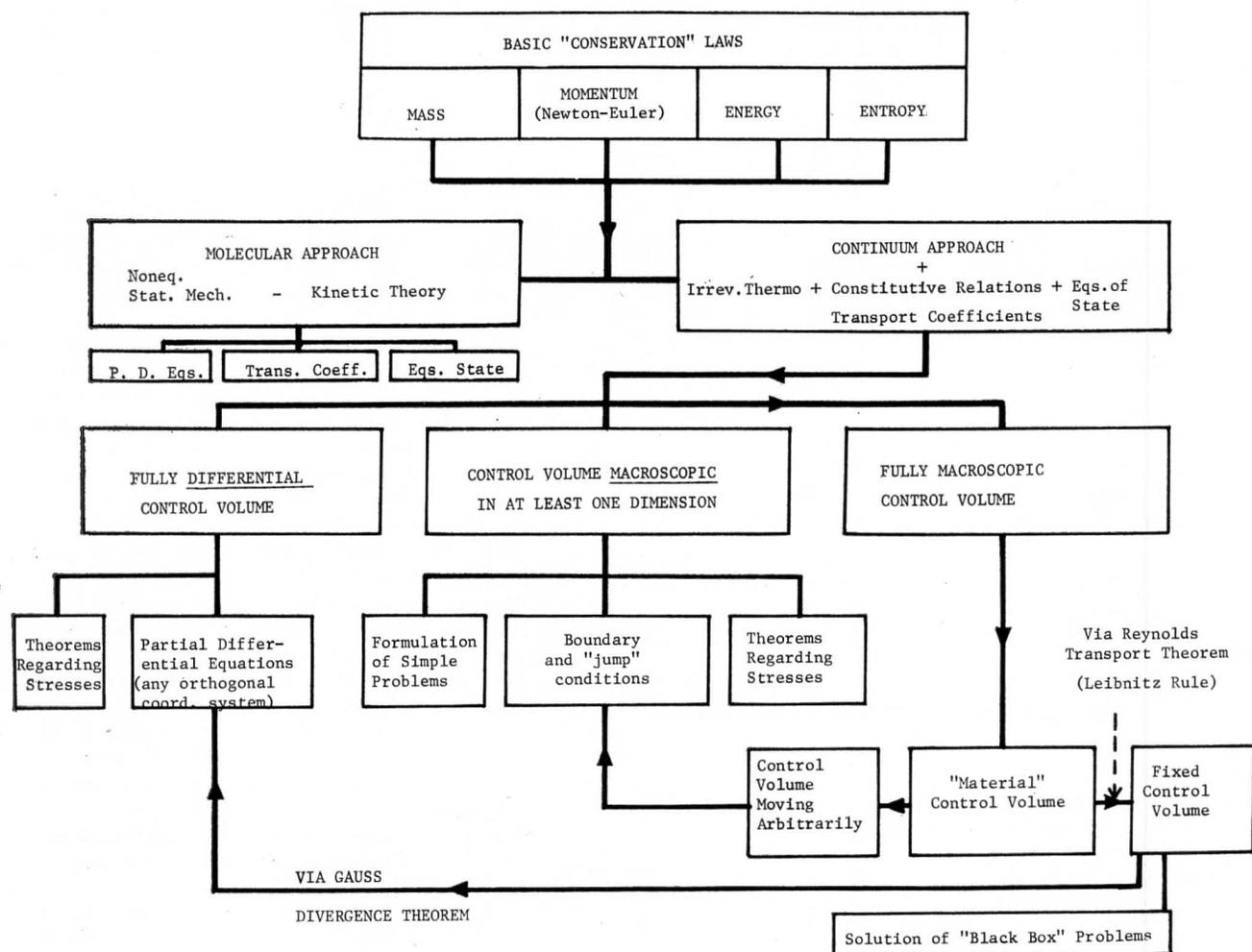
LECTURE EMPHASIS: A GENERAL METHOD

IN THE OUTLINE for this lecture (including a list of useful references [5, 6]), distributed to each student, a systematic procedure for deriving relations between field quantities on either side of surfaces of discontinuity is sketched. During the lecture this procedure is illustrated for each primary "balanced" quantity (chemical elements, chemical species mass, total mass, linear momentum, angular momentum, total energy and specific entropy) and then specialized to cases of practical

importance. For brevity we here outline the procedure as applied to chemical species conservation at interfaces, the relevant field "density" being the scalar partial density of each chemical species. Our result can then be compared to various degenerate cases stated in classical treatises on surface chemistry—e.g. Hayward and Trapnell's monograph [7] on chemisorption on solid surfaces. Using examples from recent research carried out in the Yale High Temperature Chemical Reaction Engineering Laboratories, we then consider some implications of the general boundary condition, emphasizing the important question of departures from chemical equilibrium at surfaces.

We adopt the view that the interface separates two regions (designated by \pm) each governed by continuum laws, but avoid prescribing the form of the transport laws *within* the interfacial region (owing to the magnitude of local gradients therein).*

FIGURE 1



Then:

1. Write the relevant conservation equation for an arbitrarily moving *macroscopic* control volume (since the interface motion is generally different from that of the fluid on either side of it).
2. Specialize the control volume to a "pillbox" (of arbitrary area) always moving so as to straddle the interface.
3. Evaluate all terms in the resulting integral equation [using mathematical theorems (Leibnitz, Gauss), exploiting the fact that, for sufficiently thin interfaces, the pillbox top and bottom become locally parallel (hence their unit outward normals \mathbf{n}_+ , \mathbf{n}_- are opposite in sign)].

When applied to a chemical species i present with instantaneous mass ρ_i'' per unit area of interface† and produced at the instantaneous (heterogeneous reaction) rate r_i'' per unit (projected) interface area, we obtain

$$\underbrace{\partial \rho_i'' / \partial t}_1 + \underbrace{\text{div}'' \cdot (\rho_i'' \mathbf{v}_{s,t} + \mathbf{j}_i')}_2 + \underbrace{[\rho_i''' (\mathbf{v} - \mathbf{v}_s) + \mathbf{j}_i''] \cdot \mathbf{n}_+}_3 = r_i'' \quad (1)$$

where term 1 is the accumulation rate, 2 is the net outflow of species i per unit interfacial area due to both tangential *surface* convection $\mathbf{v}_{s,t}$ and *surface* diffusion \mathbf{j}_i' 3 (involving the "jump" operator [] $\equiv ()_+ - ()_-$) is the net outflow of species i due to relative convection and diffusion normal to the interface. In comparing this relation to its better known three-dimensional analog:

$$\partial \rho_i''' / \partial t + \text{div}''' \cdot (\rho_i''' \mathbf{v} + \mathbf{j}_i''') = r_i''' \quad (2)$$

note that, in effect, the net outflow (by convection and diffusion) term per unit interfacial area in Eq. (1) has been decomposed into a tangential contribution 2 and a normal contribution 3.

IMPLICATIONS

DISSOCIATIVE chemisorption of oxygen on solid surfaces is an important elementary step in solid-catalyzed oxidation reactions. The kinetics of this step are often studied under transient conditions such that only term 1 contributes to the

*Alternate methods can be used if the "interface" is itself a continuum zone with merely large spatial gradients in one (normal) direction, and moderate spatial gradients in the tangential directions. Decomposition of the ∇ operator into normal (n) and tangential (t) contributions then allows formal integration of the presumed differential equations to obtain the desired "jump" relations. [8]

†We adopt the useful convention that triple primed ('''), double primed (') and single primed (') quantities refer, respectively, to quantities reckoned per unit volume, area and length.

... a systematic formulation of jump conditions provides insight into failure of the commonly encountered assumption of interphase local chemical equilibrium despite conditions of net chemical species transport.

left hand side of Eq. (1)—*ie.* the net rate of formation of adsorbed O-atoms is then proportional to the instantaneous rate of increase of surface coverage. [7] But if O-atom diffusion into the bulk "solvent" is important, term 3 contributes, and in molecular beam studies (in which only a portion of the target is "illuminated") [10] term 2 (surface diffusion) must be considered. We recently completed a kinetic study of the oxygen/tantalum reaction in the temperature range 1200-3000K using a transient (resistance "relaxation") method. [9] In considering Eq. (1) for atomic oxygen, term 1 contributed due to the transient, term 2 contributed due to the continuous shrinkage of the tantalum filament associated with metal gasification, and term 3 contributed due to internal dissolution of oxygen in the metal. This system* provides a dramatic illustration of the moral: be wary of unrestricted statements of highly degenerate cases of Eq. (1), such as the commonly seen forms:

$$\partial \rho_i'' / \partial t = r_i'' \quad (\text{in chemisorption}) \quad (3)$$

or

$$\mathbf{j}_{i+}'' \cdot \mathbf{n}_+ = r_i'' \quad (\text{in steady-state catalysis}) \quad (4)$$

It should also be remarked that a systematic formulation of jump conditions such as Eq. (1) provides insight into failure of the commonly encountered assumption of interphase local chemical equilibrium despite conditions of net chemical species transport. For when one descends to the molecular level one finds that each r_i'' is itself the algebraic sum of positive and negative contributions which vanish only at equilibrium. It follows that when the left hand side of Eq. (1) is non-zero then local interface equilibrium cannot be strictly valid. Thus, in any particular application the importance of this departure can be assessed, provided the relevant kinetic and transport coefficients are known or estimable. Moreover, while

*An analogous situation, recently treated by Pierson and Whitaker [11], is the surfactant (heptanoic acid) absorption mass balance for a growing droplet (water).

discussed here for the case of chemical equilibrium, similar arguments apply to the case of mechanical equilibrium (via momentum conservation) and thermal equilibrium (via energy conservation). Indeed, in a recent study [12] of the non-equilibrium crystallization of pure ZrO_2 , liquid/solid interface temperatures some 570K below the equilibrium melting point have been encountered!

CONCLUSIONS

THE TREATMENT of boundary conditions briefly described above [13] has been used to illustrate our approach to the teaching of energy, mass and momentum transport at the graduate level. We believe that such a fundamental approach to each of the topics (Table 1) is essential to the development of PhD chemical engineers who will be able to deal rationally with novel chemical processes involving extreme conditions.

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REYNOLDS: Engineer as Entrepreneur Continued from page 189.

development to commercialization.

One of the problems which necessarily arises in a one-semester course of this type is that four months is really inadequate to carry out the development and preliminary commercialization satisfactorily. Serious consideration is being given to the extension of the one-semester course to a two-semester course in which at time intervals, prototype devices could be manufactured and test marketing carried out. The current one-semester course carried three credits and has generated a great deal of interest.

The Chemical Engineering Department feels that this type of innovative course could have major beneficial effects for the Commonwealth of Massachusetts by drawing attention of engineering students to the field of entrepreneurship and to give embryonic entrepreneurs a real-life experience in the development and marketing of new products. It is hoped that as time goes on, funding may be available for "seed money" in which to take one or more of the more promising products or services into at least preliminary commercialization. □

ACADEMIC POSITIONS

For advertising rates contact Ms. B. J. Neelands, CEE c/o Chemical Engineering Dept., University of Florida, Gainesville, FL. 32601.

CHEMICAL ENGINEERING CHAIRPERSON POSITION

Candidates for the chairperson of the Department of Chemical Engineering at the State University of New York at Buffalo are being sought. Persons interested are invited to send their credentials, and persons wishing to nominate others are invited to send names and addresses to: McAllister H. Hull, Jr., Dean, Graduate School, State University of New York at Buffalo, Buffalo, NY 14214. The university is aggressively engaged in an affirmative action program and is an equal opportunity employer.

IMPLEMENTATION OF SI UNITS IN CHEMICAL ENGINEERING EDUCATION

GORDON R. YOUNGQUIST
Clarkson College of Technology
Potsdam, New York 13676

RECENT LEGISLATION passed by Congress and signed by President Ford provides for the voluntary conversion to the SI system of units in the United States. No time limit was set for the changeover, but considerable progress has already been made, especially in industries which are international.

The American Institute of Chemical Engineers has established a Metrication Committee to examine the problems of conversion to metric practice by the chemical industries. In January 1976, on behalf of this Committee, a questionnaire was sent to all U.S. Chemical Engineering Departments on the AIChE Faculties list to assess implementation of SI in chemical engineering education in the United States. 92 departments have responded and the results of the survey are summarized below. Of those responding:

- 30% indicated that their engineering schools have established policy with respect to use of SI in its courses, while an additional 15% will establish such policy in the near future.
- Where such engineering school policy exists, the policy is typically weak: the use of SI in courses is urged, but at the instructor's option. Only 3 schools indicated that some use of SI was required in all engineering courses.
- 30% of engineering schools have made some concerted efforts to introduce SI, usually by distribution of pamphlets, but also through short courses, films, seminars, and committees to respond to questions and provide other assistance.
- 49% of the ChE Departments have made some special efforts to introduce SI to their curricula, usually in at least one course (e.g., material and energy balances) and along with other systems of measurements.
 - 5 departments require some use of SI in all their courses (none use it exclusively).
 - 28% urge (but don't require) their faculty to use SI where possible.
 - 13% have distributed pamphlets or other written information on SI.
 - 26% intend to make stronger efforts in the future especially as more textbooks in SI become available.
 - 64% introduce SI along with other systems of measurement at the option of instructors.

- 68% said that at least some of its faculty write up their research and are conducting current research using SI.
- 54% indicated that their support staff (secretaries, technicians, e.g.) no working knowledge of SI, with 37% having some working knowledge.
- 51% indicated that their present seniors have a working knowledge of SI, an additional 15% a limited knowledge.
- 40% of the ChE departments thought it appropriate for accreditation groups to encourage implementation of SI, 60% did not (some quite vehemently!).
- 10% have encountered or foresaw no problems in implementing SI; the remainder cited as problems:
 - 60%, lack of texts and reference materials in SI.
 - 24%, faculty resistance.
 - 23%, faculty unfamiliar with SI.
 - 16%, lack of resource materials which explain system.
 - 15%, lack of AIChE guidance.
 - 36%, lack of national legal requirement.
 - 4%, apathy.
 - 10%, SI a lousy system.
- 17% favored immediate changeover to SI for all AIChE publications, 68% did not.
- 73% favored a phased changeover to SI for AIChE publications, 14% did not.
- 52% favored encouragement from AIChE to publishers to provide textbooks and reference materials in SI, 22% did not, and a few favored dual notation.
- 67% favored publication of an AIChE guide to metric practice, 17% did not. (The cost of such guide was questioned several times.)

SOME COMMENTS

It is evident that the transition to SI is well under way in a large number of ChE departments in the U.S., although some resistance to the SI system still exists. Most departments seem to view SI as yet another system of measurement that chemical engineers must be able to deal with, and feel that chemical engineers will need to be conversant in a variety of systems for some years to come. The major deterrent to increased use of SI in ChE education appears to be the lack of textbooks and reference materials which make use of SI. Several who responded questioned whether industrial demands for employees with SI training existed. In this respect it should be noted that some companies (Exxon, for example) have essentially completed their conversion to SI, while others have not yet addressed the problem. □

Principles of Quantum Chemistry

By D. V. George

Pergamon Press, 1972

Reviewed by Phillip Certain,
University of Wisconsin

The first thing one notices about this book is the unusual photograph on the dustjacket. A careful reading of the book gives absolutely no information about what the subject of the photograph (an electron micrograph of a mitochondria membrane?) might be. Instead one discovers that this text is a straightforward presentation of the fundamentals of quantum chemistry, pitched at a level appropriate to advanced (and bright!) undergraduates.

It is a very compact presentation, requiring only 260 pages to cover most of the topics normally treated in a course on quantum chemistry and spectroscopy. The book begins with a brief historical introduction to quantum mechanics, including a "derivation" of the Schrödinger equation based on de Broglie's wave hypothesis. After the particle-in-a-box is treated, the postulational approach to quantum mechanics is presented in a very nice way. There is a good discussion of the significance of the commutator of two operators with respect to the uncertainty principle; and a simple introduction to Dirac notation is included.

As simple applications of quantum mechanics, George considers the usual rigid rotator, harmonic oscillator, and hydrogen atom. He presents the ladder-operator approach to the eigenvalues of the angular momentum operator, and develops the eigenfunctions from the differential equations approach.

Two additional chapters are included to provide necessary background for quantum chemistry. One is a very brief discussion of variation and perturbation methods and the other is an introduction to group theory.

This basic material constitutes the first half of the book. The remaining half is devoted to discussions of many-electron atoms, molecular orbital and valence bond theory, Hückel molecular orbital theory, ligand field theory and spectroscopy. These subjects receive an average of 20 pages each, so that it is evident the author maintains his concise presentation throughout.

Given the limited space available, George treats his subject clearly and concisely. There are some very attractive features of the book. Not a great deal of mathematical background is assumed for the student. Although the presentation is distinctly mathematical, the math is carefully done and more advanced techniques are discussed separately before applications are presented. There is a concise summary and set of exercises at the end of each chapter. The style of writing is informal and readable.

The essentials are in the book, but detailed applications and explanations in general have been sacrificed to conserve space. The instructor who chooses this book as a text should be prepared to provide a fair amount of supplementary material to the students. The book might be most useful in a free-wheeling course in which the instructor wants a text for the students which is a concise reference on the fundamentals.

The book is similar in length and level of presentation to M. W. Hanna's *Quantum Mechanics in Chemistry* [Benjamin (1969)]. The experience of our undergraduate students with this latter book is that, without substantial initial help, its conciseness is a real barrier to understanding. □

Optimization by Variational Methods

By Morton M. Denn

McGraw-Hill Book Company, New York, 1969

Reviewed by E. Stanley Lee, University of Southern California

Many books on optimization have been published. But, unfortunately, most books are not written for chemical engineers and do not use chemical engineering systems as examples. This book fulfills this gap in the variational approach. Furthermore, it is well written and has many useful examples.

Variational methods cover many different areas and frequently involve fairly sophisticated mathematics. Professor Denn did an excellent job in presenting the material and in avoiding the requirement of more sophisticated mathematical background. However, the user of this book must be cautioned about the fact that many chemical engineering students do not have the mathematical maturity and the teacher must present the material in great detail during the initial period. More homework and problem solv-

ing periods in class also help the situation.

Chapter 1 presents the basic concepts of optimization by differential calculus, also known as single stage optimization by differential calculus. It provides a useful and easy transition from differential calculus for the optimization of finite number of variables to the variational calculus for the optimization of functionals. The latter is treated in Chapters 3 to 6 for continuous systems and in Chapter 7 for staged systems. Computational problems are treated in Chapter 9 and Chapter 10 treats nonserial processes. An introductory coverage on feedback control and distributed-parameter systems is given in Chapters 8 and 11. In Chapter 12, an introduction to dynamic programming is given together with a demonstration of the interconnections between dynamic programming and the variational approaches.

In teaching a typical chemical engineering optimization course at the graduate level, this reviewer has found that it is useful to divide this course into two parts: the variational approaches and the programming approaches. The latter category includes all the linear and nonlinear programming techniques, and dynamic programming. As a foundation to these two categories, the various search techniques and numerical methods for solving algebraic and differential equations are introduced. Since practical chemical engineering problems are usually nonlinear problems; numerical solution, not analytical solution, should be emphasized.

Viewed from the above concept, this book can be used as a textbook for the variational approaches. If optimization is a one-year course, the variational approaches should be covered in a semester. The second semester is more appropriate with the first semester covering the programming techniques and the search techniques.

If the variational techniques are to be covered in one semester, fairly detailed discussions should be given to Chapters 1 and 3. The derivations in Chapters 4 and 5 can be omitted except to summarize the results to provide a transition from Chapters 3 to 6. Chapters 6, 7, 9 and 10 should, again, be covered completely. Since Chapter 2 is only an introductory chapter on search techniques which should be covered in the previous semester, this chapter can be omitted. Greater emphasis should be placed on Chapters 9 and 10. Furthermore, the material in these two chapters can be supplemented with recent publications in the literature. □

FALL 1976

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1.25 - THIS IS A LOG TABLE?

J. M. BERTY
Autoclave Engineers, Inc.
Erie, Pennsylvania 16501

$$\begin{aligned} 10^{0.1} &= 1.25 \\ 10^{0.2} &= 1.6 \\ 10^{0.3} &= 2.0 \end{aligned}$$

YES, IF YOU can remember that:

$$10^{0.1} = 1.25, \text{ and}$$

you know the rule that:

$10^{0.1} (10^{0.1}) = 10^{0.2}$, then you have memorized the log table and should be able to raise any number to any exponent, first with paper and pencil and later in your head and get an estimate of the order of magnitude and the first digit correct.

With the age of the \$20.00 electronic calculator upon us, the danger that people will soon forget even how to add is all to real. A slightly more expensive calculator can give logarithmic and exponential functions, and so the engineer's slide rule will join the abacus in the museum. Both of these are still excellent educational tools to illustrate some basic concepts and should be retained as such. The use of electronic calculators, just like the computers, will speed up getting results—both good and bad results. So checking out results, at least for order-of-magnitude correctness, is more important than ever. The following two-digit log table can help you to check the results from your calculator and from your computer.

Starting with the basic premise that:

$$10^{0.1} = 1.25^* \text{ and } 10^{0.1}(10^{0.1}) = 10^{0.2}$$

i.e., $1.25(1.25) = 1.56 \approx 1.6$ we received

$$10^{0.2} = 1.6. \text{ In the same way,}$$

$$10^{0.1}(10^{0.2}) = 10^{0.3}, \quad 1.25(1.6) = 2.0, \text{ we already calculated } 10^{0.3} = 2.00.$$

In summary:

*The four-digit value is for $10^{1.0} = 1.259$ which rounds up to 1.26 and this value is recommended for chain multiplication, i.e., $10^{0.3} = (1.26)^3$. In the following table where all other values are rounded to two digits, the value of 1.25, i.e., one and a quarter, fits better.

Carrying out the same way for all nine digits:
 $10^{0.1}(10^{0.3}) = 10^{0.4}$, $1.25(2.0) = 2.5$, or

$$10^{0.2}(10^{0.2}) = 10^{0.4}, \quad 1.6(1.6) = 2.5, \text{ etc., we}$$

receive the following table:

$10^{0.1} = 1.25$	$10^{0.4} = 2.5$	$10^{0.7} = 5.0$
$10^{0.2} = 1.6$	$10^{0.5} = 3.2$	$10^{0.8} = 6.4$
$10^{0.3} = 2.0$	$10^{0.6} = 4.0$	$10^{0.9} = 8.0$

Reconstruct this table on your blackboard daily and admire it; sooner or later it will sink into your brain.

The table is organized this way to take advantage of $10^{0.3} = 2$, so the exponents, or logs, are 0.3 higher in the second column than in the first and the numbers or anti-logs, are twice as much. The same holds for the third vs. second columns. This way is enough to remember the first column, and try to memorize only the first column at the start, but the most important thing is to remember how it was derived. A feel for the errors involved in the rounding of the antilogs to two digits will help you to know how much precision you can expect of these numbers. Therefore, look up the exact values for the antilogs of 0.1, 0.2, etc. from a log table, or from your pocket calculator. In addition, derive the higher logs from the lower ones in various ways, like $10^{0.1}(10^{0.7}) = 10^{0.8} = 1.25(5.0) = ?$ and $10^{0.4}(10^{0.4}) = 10^{0.8} = ?$ and so on. Calculate also $(10^{0.1})^{10} = 1.25(1.25)_2(1.25)_3 \dots (1.25)_{10} = ?$. Do the same for 1.26 and 1.259.

Before we start to use this table, it is useful to recall that by asking the question: "What is the log of 2?" we are asking, in essence: "To what exponent do I have to raise 10 to receive a 2?"

So let's start learning to raise numbers to fractional exponents.

EXAMPLE 1. A production unit has to be in-

creased to 4 times its present capacity. The investment cost of this type of unit is proportional to the 0.8 power of the size. How much more will the 4-times-larger unit cost than the present one?

So the question really is, $4^{0.8} = ?$

SOLUTION: $4 = 10^{0.6}$, $4^{0.8} = (10^{0.6})^{0.8} = 10^{0.6 \times 0.8} = 10^{0.48}$ and since $10^{0.5} = 3.2$ so $10^{0.48}$ will be somewhat less, let's say about 3. So a 4-times-larger unit will cost 3 times more to build. The result by calculator is 3.03.

EXAMPLE 2. Calderbank and Pogorski reported [1] for heat transfer in fluid beds that:

$$Nu = 0.36 Re^{0.36}$$

What is the Nusselt number if the Reynolds number is 200? That is, $0.36 (200)^{0.36} = ?$

SOLUTION: $200 = 2 \times 100 \approx 10^{0.3} (10^2) = 10^{2.3}$, $(10^{2.3})^{0.36} = 10^{2.3 \times 0.36} \approx 10^{0.83}$, and $0.36 = 3.6(10^{-1})$ and since $10^{0.5} = 3.2$ and $10^{0.6} = 4.0$, $0.36 \approx 10^{0.55} (10^{-1})$ or $10^{-0.45}$, finally $10^{-0.45} (10^{0.83}) = 10^{-0.45 + 0.83} = 10^{0.38}$, and since $10^{0.4} = 2.5$ and $10^{0.3} = 2.0$, $10^{0.38} \approx 2.4$. Therefore, the Nusselt number will $0.36(200)^{0.36} = 2.4$.

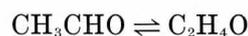
The electronic calculator gives 2.42, i.e., the error of our estimate is quite low.

COMMENTS: For numbers outside 1 and 10, we convert them to these and to the product of ten raised to an integer number. Then, for numbers between 1 and 10, we find the exponent of ten corresponding to their value from our table (mantissa of the logarithm) and add it to the integer exponent of ten (characteristic of the logarithm).

EXAMPLE 3. The isomerization of acetaldehyde to ethylene oxide in the vapor phase should

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be checked for commercial feasibility [2]. For this reaction:



the equilibrium constant at 1000°K is:

$\ln K = -17.4$. How much ethylene oxide can we expect?

$$K = e^{-17.4} = 10^{-17.4/2.3} = 10^{-7.6} = 10^{0.4} (10^{-8})$$

$$K = 2.5(10^{-8}) = 25(10^{-9}) = 25 \text{ PPB}$$

The expected ethylene oxide concentration will be a few tens PPB. Even if the tacitly assumed ideal gas assumption is wrong, it can change the results by less than an order of magnitude, and the process is not feasible.

EXAMPLE 4. What is the apparent energy of activation of ethylene hydrogenation over an Ni-catalyst if the reaction is eight times faster at 400°K than at 300°K? (3)

$$-\frac{E}{R} \left(\frac{1}{T_1} - \frac{1}{T_2} \right) = 8$$

$$-\frac{E}{(2)(1000)(2.3)} \left(\frac{1000}{400} - \frac{1000}{300} \right) = 8$$

$$-\frac{E}{4600} (2.5 - 3.333) = 8, \text{ since } 8.00 = 10^{0.9}$$

$$\frac{E}{4600} 0.833 = 0.9$$

$$E = \frac{4600(0.9)}{0.833} \approx 5000$$

The apparent energy of activation is about 5000 cal/gmole

In conclusion, with a little work and a lot of perseverance, this simple log table can be memorized and used for checking orders of magnitude.

The final advice: before you calculate anything with your calculator or computer, first make a guess as to what number to expect, then carry out the calculation and, finally, check whether the results are reasonable. □

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CHEMICAL ENGINEERING EDUCATION INDEX Volumes VI-X

AUTHOR INDEX

- A**
- Aldag, A. W. _____ VI, 36
 Alkire, R. _____ X, 126, 158
 Allen, T. _____ X, 93
 Anderson, J. B. _____ VI, 3
 Anderson, J. E. _____ VI, 92
 Andres, R. P. _____ X, 18
 Aris, R. _____ VIII, 20; IX, 99, 118,
 X, 2, 114, 124
 Astarita, G. _____ IX, 152
- B**
- Bailey, J. E. _____ X, 162
 Balch, C. W. _____ VI, 23
 Balzhiser, R. E. _____ VI, 40
 Bankoff, S. G. _____ VI, 49
 Barker, D. H. _____ VI, 25
 Bell, K. J. _____ VI, 154
 Bennett, G. F. _____ VIII, 82
 Berg, L. _____ VI, 8
 Bergantz, J. A. _____ VII, 112
 Bernier, C. L. _____ IX, 194
 Bert, J. M. _____ X, 198
 Biery, J. C. _____ IX, 198; X, 94
 Black, J. H. _____ IX, 143
 Brown, B. A. _____ IX, 76
 Burnet, G. _____ VI, 62
- C**
- Cadman, T. W. _____ VII, 33; VIII,
 120; IX, 68
 Carberry, J. J. _____ VII, 22; X, 107
 Carnahan, B. _____ VII, 80
 Cassiere, G. _____ VII, 22
 Certain, P. _____ X, 194
 Chao, K. C. _____ VI, 158
 Chen, T. Y. _____ IX, 10
 Checrick, M. H. _____ VIII, 58, IX, 128
 Clark, J. P. _____ X, 90
 Cloutier, L. _____ VII, 38
 Cobb, Jr., J. T. _____ VI, 143
 Cohen, R. E. _____ VII, 30; X, 44
 Cokelet, G. R. _____ VII, 76
 Cooney, D. O. _____ VI, 162
 Copeland, N. A. _____ VIII, 66
 Corcoran, W. H. _____ VII, 187
 Corripio, A. B. _____ VIII, 162
 Cosart, W. P. _____ X, 134
 Cunningham, R. C. _____ VII, 18
 Curl, R. L. _____ VI, 166
- D**
- Dahlstrom, D. A. _____ VII, 187
 Daniels, R. D. _____ VII, 164
 Daubert, T. E. _____ VII, 84, 187
 DeFore, J. J. _____ VI, 62
 DeNevers, N. _____ VII, 126; VIII, 98;
 X, 16
 Delgass, W. N. _____ VI, 124; IX, 62,
 158
- Denn, M. M. _____ VII, 117, 208; X, 196
 Deshpande, P. B. _____ IX, 88; X, 168
 Donaghey, L. F. _____ VIII, 164;
 IX, 192
 Douglas, J. M. _____ VI, 180; IX, 8
 Dunn, I. J. _____ X, 23
- E**
- Eakman, J. M. _____ VIII, 116
 Edgar, T. F. _____ VIII, 168
 Ernst, W. R. _____ X, 146
 Eubank, P. T. _____ VI, 30
 Evans, T. F. _____ VI, 88
- F**
- Fahien, R. W. _____ VI, 45, 147; VII,
 155; VIII, 159; IX, 151, 198; X, 155
 Fan, L. T. _____ IX, 120
 Feinberg, M. _____ X, 125
 Felder, R. M. _____ VI, 118, 132
 Finger, S. M. _____ IX, 68
 Fogler, H. S. _____ VII, 122
 Foss, A. S. _____ VII, 72
 Fredenslund, A. _____ VII, 142
 Frederickson, A. G. _____ VI, 36
 Freshwater, D. C. _____ VI, 190
 Fricke, A. L. _____ VII, 176
 Fulford, G. D. _____ VI, 128
- G**
- Gaden, Jr., E. L. _____ IX, 40
 Gainer, J. L. _____ VI, 171
 Gangi, A. F. _____ VI, 30
 Gardner, R. P. _____ VII, 132
 Gates, B. C. _____ VIII, 172; IX, 124
 Gerrard, A. M. _____ IX, 28
 Gill, W. N. _____ IX, 194; X, 107
 Gluckman, M. J. _____ VIII, 82
 Godbold, T. M. _____ IX, 16
 Good, R. J. _____ X, 16
 Graessley, W. W. _____ VI, 127
 Greenkorn, R. A. _____ VI, 158;
 VIII, 176
 Grens, E. A. _____ VII, 72
 Griskey, R. G. _____ X, 48, 140
 Gruver, W. A. _____ IX, 162
 Gryte, C. C. _____ X, 28
 Gubbins, K. E. _____ VII, 203
 Gupta, L. _____ VII, 200
- H**
- Haering, E. R. _____ VIII, 74
 Hall, K. R. _____ IX, 24
 Halligan, J. E. _____ VII, 158
 Hamrin, C. E. _____ VIII, 200
 Han, C. D. _____ VI, 74
 Hawley, M. C. _____ VI, 110;
 IX, 128
 Heenan, W. A. _____ X, 17
 Henley, E. J. _____ X, 17
- Henry, Jr., J. D. _____ VII, 208
 Henry, J. M. _____ VI, 132
 Hershey, J. _____ VII, 106
 Hile, L. R. _____ X, 18
 Hill, C. T. _____ VII, 184
 Hladky, W. _____ VI, 122
 Hoffman, T. W. _____ VII, 96
 Hopfenberg, H. B. _____ VII, 174
 Howard, G. M. _____ VIII, 82
 Hubbard, D. W. _____ X, 76
 Hudgins, R. R. _____ IX, 138
 Hughes, R. R. _____ VII, 28
 Hunt, R. G. _____ IX, 194
 Hunter, D. L. _____ VII, 14
- I**
- Ingham, J. _____ X, 23
 Isakoff, S. E. _____ VII, 84
- J**
- Jacobs, L. J. _____ X, 5
 Johnson, A. I. _____ VII, 96
 Johnson, E. F. _____ X, 172
 Jorne, J. _____ IX, 31
- K**
- Kabel, R. L. _____ VI, 88
 Kadlec, R. H. _____ VI, 166, VII, 110
 Kafes, N. _____ VI, 178
 Kapner, W. H. _____ VI, 4
 Katzer, J. R. _____ VIII, 172
 Kelleher, E. G. _____ VI, 178
 Keppel, R. A. _____ VI, 45
 Kermod, R. I. _____ VIII, 200
 Kessler, D. P. _____ VIII, 176
 King, C. J. _____ VI, 50; VII, 72;
 VIII, 6; X, 56
 Kirk, R. S. _____ VI, 35; VIII, 90
 Kirwan, D. J. _____ IX, 24
 Kittrell, J. R. _____ VI, 180
 Klinzing, G. E. _____ X, 176
 Koutsky, J. A. _____ X, 184
 Kranich, W. L. _____ VIII, 12; X, 70
 Kube, W. R. _____ VI, 111
 Kushner, J. _____ VI, 66
- L**
- Lamping, N. E. _____ VI, 30
 Lapidus, L. _____ VI, 148
 Larsen, A. H. _____ VIII, 70
 Larson, M. A. _____ VI, 70; VIII,
 78; IX, 201; X, 108
 Lashmet, P. K. _____ VIII, 130
 Lastovica, J. E. _____ VII, 198
 Laurence, R. _____ X, 112
 Lees, F. P. _____ VI, 190
 Leflich, R. _____ X, 180
 Levenspiel, O. _____ IX, 102
 Leggett, Jr., L. W. _____ VI, 36
 Leinroth, Jr., J. P. _____ VI, 80

Lightsey, G. R. IX, 144
 Lin, S. H. IX, 120
 Liu, Y. A. IX, 166
 Locke, C. E. VII, 164
 Lockhart, F. J. X, 154
 Lohmann, M. R. VII, 187
 Long, R. B. VII, 87
 Lovinger, A. J. X, 28
 Luks, K. D. VIII, 180
 Luss, D. VII, 16; VIII, 102
 Lynn, S. VII, 72

M

Ma, Y. H. VIII, 12
 Maddox, R. N. VII, 66
 Manning, F. S. IX, 170
 Marchello, J. VII, 56
 Martin, J. B. VIII, 74
 Martin, J. J. VIII, 138
 Mason, D. M. VI, 102
 Matthews, M. A. IX, 76
 McCoy, B. J. IX, 174
 McGee, Jr., H. A. IX, 52
 Meisen, A. VII, 144
 Mellichamp, D. A. VII, 146
 Melnyk, P. B. VIII, 184
 Meredith, R. E. VII, 55
 Merrill, E. W. X, 44
 Merrill, R. P. VII, 161
 Miller, A. D. X, 33
 Miller, C. W. VII, 33
 Miller, J. D. X, 84
 Mischka, R. A. VI, 114
 Modell, M. IX, 106
 Moo-Young, M. IX, 4
 Moore, C. F. VII, 168
 Murray, F. VIII, 58

N

Nelson, Jr. R. D. IX, 66
 Newman, J. A. VI, 194

O

O'Connell, J. P. VII, 203
 Oden, E. C. VIII, 16, 134
 Ollis, D. F. X, 162
 Olson, J. H. VIII, 172
 Overholser, K. A. IX, 16

P

Parker, R. O. VI, 4
 Paul, J. F. VII, 40; VIII, 94
 Pei, D. C. T. VI, 128
 Perna, A. J. VII, 122; IX, 150
 Peters, M. S. VII, 187

A

Administration of Engineering and
 Technical Personnel IX, 180
 Adsorptive Bubble Separation
 Methods X, 180
 Advanced Thermodynamics VIII, 180

Petty, D. S. X, 33
 Pham, C. VII, 38
 Pings, C. J. VII, 92; VIII, 70
 Polack, J. A. IX, 180
 Prausnitz, J. M. VI, 60; VII, 203;
 VIII, 6; X, 60
 Prenosil, J. E. X, 23
 Prober, R. VIII, 184
 Pulsifer, A. H. VI, 78

R

Rase, H. F. IX, 22
 Ray, W. H. X, 154
 Regan, T. M. IX, 68
 Rehm, T. R. X, 84
 Reilly, P. VIII, 116
 Reynolds, H. H. X, 188
 Rhodes, E. VIII, 44; IX, 84
 Richardson, J. T. VII, 16
 Rigaud, M. IX, 184
 Robertus, R. J. X, 80
 Rosen, E. M. VIII, 48
 Rosner, D. E. X, 190
 Rousseau, R. W. VII, 132
 Rudd, D. F. VII, 44, 72
 Russell, T. W. F. VII, 117
 Rutherford, A. IX, 118
 Rutkowski, M. A. IX, 88

S

Sandall, O. C. VI, 28; VII, 146
 Sandler, S. X, 40
 Schmitz, R. A. VII, 136
 Schowalter, W. R. VI, 8; VII, 54
 Schreiber, H. P. IX, 184
 Schrodt, V. N. VIII, 200; IX, 183
 Schuitt, G. A. A. VIII, 172
 Seagrave, R. C. VI, 70;
 VII, 76; X, 108
 Shah, D. O. VIII, 32
 Shaheen, E. I. IX, 128
 Shair, F. H. VII, 122
 Shelden, R. A. X, 130
 Sherman, J. D. IX, 124
 Sherwood, T. K. VIII, 204
 Shuster, C. N. VII, 209
 Silla, H. VII, 129
 Slattery, J. C. VI, 174
 Sleicher, C. A. IX, 2
 Smith, J. M. VII, 4
 Sommerfeld, J. T. VII, 18; X, 90,
 146
 Sorensen, K. D. VIII, 130
 Storvick, T. S. VIII, 40

Strunk, M. R. VII, 156
 Sussman, M. V. VIII, 149
 Sutterby, J. L. VI, 188

T

Tao, L. C. VI, 139
 Tavlarides, L. L. VIII, 188
 Thatcher, C. M. VIII, 146
 Thies, C. VIII, 194
 Tierney, J. W. VII, 180
 Tiller, F. M. IX, 115
 Timm, D. C. VIII, 116
 Timmerhaus, K. D. VI, 83
 Treybal, R. E. VI, 4
 Tschoegl, N. W. VII, 30
 Tucker, W. H. VIII, 142; X, 36
 Tyner, M. VI, 45

U

Ulrichson, D. L. VIII, 78
 Updike, O. L. IX, 24

V

Vermeulen, T. VIII, 6
 Vermeychuk, J. G. VII, 112
 Vivian, J. E. VII, 89

W

Walawender, W. P. IX, 10
 Walker, C. A. VI, 124, 150
 Walter, C. F. IX, 188
 Ward, T. J. X, 136
 Ware, Jr., C. H. IX, 62
 Wasan, D. T. VII, 200
 Watson, F. A. VII, 54
 Watt, Jr., D. M. VI, 80
 Wei, J. VIII, 172
 Weller, S. W. X, 74
 West, J. B. VII, 66
 Westwater, J. W. X, 6, 154
 Wheelock, T. D. VI, 106
 Whitwell, J. C. VI, 148
 Wilde, D. IX, 139
 Wilkes, J. O. VII, 80
 Williams, R. D. VII, 148;
 VIII, 28 IX, 133; X, 134
 Wolf, D. IX, 133
 Woltz, C. C. IX, 16
 Woods, D. R. VII, 96; VIII, 82

Y

Youngquist, G. R. IX, 32; X, 195

Z

Zwiebel, I. VIII, 12; X, 70

TITLE INDEX

Advanced Chemical Engineering at
 Loughborough VI, 191
 AIChE Annual Report VI, 49
 AIChE Career Guidance
 Committee VI, 122
 Alkaline Fading of Organic Dyes:
 An Ideal Reaction for Homogen-

ous Reactor Experiments X, 18
 Analog Simulation of Sampled-Data
 Control Systems IX, 88
 Analog Simulation of the Dispersion
 of Atmospheric Pollutants VII, 33
 Applications of Heterogeneous
 Catalysis VII, 16

Application of Molecular Concepts of Predicting Properties Needed for Design VII, 203
 Application of Perturbation Techniques to Analog Computations VIII, 94
 Applied Chemical Kinetics VII, 161
 Applied Surface Chemistry, A Course in VI, 171
 Art and Science of Rheology, The VI, 14
 Associate Degree ChE Technology Programs VI, 66

B

Baccalaureate Programs in Chemical Engineering Technology VI, 62
 Bernoulli's Equation with Friction VII, 126
 Beckman, Bob—ChE Educator VII, 56
 Biochemical Engineering Fundamentals X, 162
 Biological Reactions: Kinetics of Yeast Growth VI, 134
 Biological Transport Phenomena and Biomedical Engineering, A Survey Course in VI, 162
 Biotechnology—An Old Solution to New Problems IX, 40
 Book Reviews:
 ChE Thermodynamics: The Study of Energy, Entropy and Equilibrium VIII, 41
 Chemical Kinetics and Reactor Design VIII, 102
 Chemical Plant Simulation VII, 28
 Dynamic Behavior of Processes VII, 208
 Environment, Power and Society VII, 209
 From Electrocatalysis to Fuel Cells VII, 55
 Fundamentals and Modeling of Separation Processes, Absorption, Distillation, Evaporation and Extraction IX, 183
 Heat and Mass Transfer Data Book X, 154
 Introduction to Chemical Engineering Analysis VII, 110
 Introduction to Control Systems IX, 139
 Introduction to Nonlinear Continuum Thermodynamics, An X, 125
 Introduction to Process Economics IX, 143
 Introduction to Thermodynamics: Classical and Statistical VI, 60
 Mathematical Methods of Chemical Engineering, Vol. 3 Process Modeling Estimation and Identification IX, 99
 Mathematics Applied to Deter-

ministic Problems in the Natural Sciences X, 124
 Mixing—Principles and Applications X, 5
 Modeling Crystal Growth Rate from Solution IX, 201
 Multivariable Computer Control X, 154
 Optimization by Variational Methods X, 196
 Polymer Science and Engineering VI, 127
 Polymers in Engineering Curriculum VII, 54
 Principles of Quantum Chemistry X, 196
 Process Synthesis VIII, 146
 Processes and Systems in Industrial Chemistry VI, 35
 Staged Cascades in Chemical Processes VII, 208
 Transport Phenomena for Engineers VI, 188
 Buffalo—SUNY, ChE Department VII, 112
 Building a Computer Program: Multi-component Distillation VI, 80

C

Can an Engineer Be Actualized? X, 94
 Carberry, James J., ChE Educator VIII, 2
 Carberry's Ultimate Paper IX, 118
 Career Guidance and Recruitment at Michigan State VI, 110
 Career Guidance and Recruitment at Virginia Polytechnic Institute VI, 114
 Changing Role of the Chemical Engineer, The VIII, 66
 Chemi Project, The X, 17
 Chemical Process Design and Engineering Summer School Workshop VII, 72
 Chemistry of Catalytic Processes VIII, 172
 Combustion Project: Explosive Limits X, 40
 Comments on a Proctorial System of Instruction VI, 78
 Comments on Gibbs Equation: The Condition for Chemical Equilibrium in Open Systems VIII, 70
 Computerized Cost Engineering in the Process Design Course VIII, 120
 Computerized Undergraduate Process Dynamics and Control Laboratory VII, 136
 Corrosion Control VII, 164
 Cost Estimating by Computer in Process Design VIII, 130
 Critical Path Planning of Graduate

Research IX, 192

D

Demonstrating Catalytic Reactor Stability IX, 138
 Deriving Three Thermodynamic Equations in Vapor-Liquid Equilibrium Studies VI, 139
 Design Laboratory, The Chemical Engineering VII, 129
 Design of Process Control Systems Using Frequency Response and Analog Simulation Techniques VII, 40
 Development of Mass Transfer Theory VIII, 204
 Diamonds Are a Thermodynamicist's Best Friend IX, 66
 Digital Computations for Chemical Engineers IX, 166
 Digital Computer Control of Processes VIII, 162
 Digital Computer Process Control VII, 168
 Digital Simulation X, 23
 Distillation Dynamics and Control X, 168
 Diversified and Special Programs in Undergraduate Chemical Engineering Education VI, 45
 Douglas, James, ChE Educator X, 112
 Dynamical Systems and Multivariable Control—An Operations Research Approach to Automatic Control Education XI, 162

E

Economics of the Chemical Processing Industries VII, 172
 Education for the Seventies, Chemical Engineering VI, 40
 Education Projects Committee, Chemical Engineering VI, 50
 Effectiveness of Graduate Chemical Engineering Education—Academic Viewpoint VII, 89, 92
 Effectiveness of Graduate Chemical Engineering Education—Industrial Viewpoint VII, 84, 87
 Effectiveness of Graduate Chemical Engineering Education—Industrial Versus Academic Viewpoint VII, 84
 Electrochemical Engineering X, 158
 Energy Engineering VIII, 200
 Energy, Mass and Momentum Transport X, 190
 Engineer as an Entrepreneur, The X, 188
 Engineering Entrepreneurship, A Course in VI, 181
 Environmental Courses X, 176
 Enzyme and Biochemical Engi-

neering VIII, 188
 Enzyme Catalysis IX, 188
 Equilibrium Theory of Fluids, A
 Course in VI, 158
 Evolutionary Experiment,
 An VII, 144
 Expansion and Contraction Losses in
 Fluid Flow VIII, 138
 Experiments in Heterogeneous
 Catalysis IX, 124

F

Flow Curve Determination for Non-
 Newtonian Fluids IX, 10
 Flow Modeling and Parameter Esti-
 mation Using Radiotracers VII, 132
 Food Engineering X, 166
 Forced Convection Demonstration
 Using Solid CO₂ Sublimation,
 A VII, 146
 Foreign Language Requirements for
 the Ph.D. VI, 88
 Foreign Study Program in Chemical
 Engineering, A VIII, 78
 Freshman Engineering—A Student
 Viewpoint VII, 14
 Fusion Reactor Technology ... X, 172

G

Georgia Tech's Pulp and Paper
 Engineering Program IX, 145
 Graduate School—Who Should
 Go? VII, 158

H

Happel, John, ChE Educator ... VI, 4
 Heterogeneous Catalysis ... IX, 158
 Horn, Fritz, ChE Educator ... VI, 54
 Hot Lips, A Cold Heart and
 Thermometry IX, 102
 How to Get the Most Out of an
 Equation without Really
 Trying X, 114

I

Identity, Breadth, Depth in a Co-
 operative Program IX, 84
 Illinois, Urbana, ChE Depart-
 ment X, 6
 Implementation of SI Units in ChE
 Education X, 195
 Implementing Changes in Engineer-
 ing Education VI, 92
 Improving College Teaching in
 Chemical Engineering VI, 132
 Index, Volumes VI-X X, 200
 Indirect Measurement of Reaction
 Rate VIII, 2
 Industrial Pollution Control IX, 170
 Industrial Researcher Looks at the
 Master's Degree, An VII, 198
 Inexpensive Time Bomb, An VIII, 98
 Integrated Reactor Engineering

Laboratory, An VII, 148
 Integration of Biomedical and En-
 vironmental Examples into Under-
 graduate ChE Course Work VII, 76
 Interfacial Phenomena for Engineers
 —A Bridge Between Engineering
 Life Sciences VIII, 32
 Interphase Catalytic Effectiveness
 Factor: Activity, Yield and Non-
 isothermality, The VII, 22
 Instruction by the PSI Method in a
 Required Senior Course ... X, 76
 Introducing Behavioral Science Into
 an Engineering Laboratory VIII, 74
 Introduction to Chemical Engineering
 Analysis VII, 117
 Introductory Design Course for
 Engineering Freshmen, An IX, 32
 Introductory Polymer Science and
 Technology X, 184
 Iowa State, ChE Department X, 108
 Ivory Tower Man Dines in the Real
 World, An X, 80

J

Jackson, Julius J., In
 Memoriam IX, 31
 Junior Course in Chemical Engi-
 neering Computations, A VIII, 48

L

Littlejohn, C. E., In
 Memoriam IX, 150

M

M.I.T.'s Polymer Program X, 44
 Measures of Excellence of Engineer-
 ing and Science Departments: A
 Chemical Engineering
 Example IX, 194
 Michigan, ChE Department VII, 60
 Michigan State, ChE
 Department VIII, 58
 Modeling, A Course in VI, 166
 Modern Analysis Techniques with the
 APL System VII, 38
 Modern Thermodynamics ... IX, 152
 Molecular Thermodynamics for
 Chemical Process Design ... X, 60
 Montana State, ChE
 Department VI, 8
 Motivating for ChE VI, 111
 Multi-purpose Video-Taped Course
 in Data Analysis VIII, 176
 Multivariable Control and
 Estimation VIII, 168

N

Nebraska's Integrated Process De-
 velopment/Design
 Laboratory VIII, 116
 Network Planning and the ChE
 Curriculum VII, 18

New Look, A, ChE Lab IX, 8
 New Traditional Unit Operations
 Laboratory Course, A ... VII, 142
 Newark College of Engineering,
 ChE Department IX, 56
 Non-Isothermal Tubular Reactor
 Program VIII, 90
 Numerical Methods for Chemical
 Engineering Problems VII, 80

O

O'Connell, John P., ChE
 Educator X, 14
 Ohio State, ChE
 Department VIII, 106
 Organic and Physical Chemistry
 Courses in 89 ChE Curricula VI, 143
 Organization of Reaction Engineer-
 ing Problems X, 146

P

Packed Column Mass Transfer Co-
 efficients for Concurrent and
 Countercurrent Flow: An Analysis
 of Recent Work X, 84
 Peaceful Coexistence of Engineering
 and Technology in the
 University VI, 70
 Pings, Neal, ChE Educator VII, 106
 Plan for Graduate Student Research
 in Engineering, A VI, 194
 Plans for Academic and Industrial
 Research Interaction VI, 83
 Plant Design: A Logical First Course
 for Freshmen X, 130
 Pollution of the Environment: Causes
 and Cures IX, 128
 Polymer Processing VII, 176
 Polymer Processing at Brooklyn
 Poly. VI, 74
 Polymer Program at Caltech,
 The VII, 30
 Polymers, Surfactants and Colloidal
 Materials VII, 174
 Practical Introduction to Analysis
 and Synthesis, A X, 134
 Prausnitz, John, ChE Educator X, 56
 Prediction of Temperature and Oxy-
 gen Distributions During Aerobic
 Microbial Growth IX, 68
 Preliminary Appraisal of a Self-Paced
 Laboratory IX, 22
 Preparing the Engineer for His
 Unique Role VI, 36
 Princeton, ChE Department ... VI, 56
 Process and Plant Design Project, A
 Course in VI, 178
 Process Heat Transfer: Sufficient
 Conclusions from Insufficient
 Premises, A Course in ... VI, 154
 Process Model-Building: An Intro-
 duction to Complex Design X, 136
 Process Synthesis VII, 44

Process Technology of Solid-State Materials and Devices VIII, 164
 Profession, The Chemical Engineering X, 126
 Profession and Cooperative Education, The Chemical Engineering VIII, 142
 Professional Program in Engineering, A VII, 66
 Project Approach to Chemical Engineering Education Under the WPI Plan VIII, 12

R

Ranking Chemical Engineering Departments X, 140
 Reid, Bob, ChE Educator IX, 106
 Reminiscences of Barnett F. Dodge VI, 150
 Review of the History of Mass Transfer VIII, 204

S

Saponification of Acetamide in a Batch Reactor X, 74
 Science of Synthetic and Biological Polymers VIII, 194
 Seagrave, Dick, ChE Educator VI, 106
 Seeing Entropy—The Incomplete Thermodynamics of the Maxwell Demon Bottle VIII, 149
 Self-Instruction in Thermodynamics IX, 115
 Separation Processes: Particulate Systems and Column Operations IX, 174
 Short Happy Life of Aris Rutherford, The IX, 119
 Should Engineering Students Be Taught to Blow the Whistle on Industry? IX, 198
 Simple, Instructive Solid State Diffusion Experiment for Use in Teaching Laboratories, A X, 33
 Simulation of the Cardiopulmonary Circulation: An Experiment in Reactor Analysis with Medical Appli-

cations X, 28
 Single Drop Liquid Extraction Experiment, A VI, 28
 Sliepcevich, Cheddy, ChE Educator IX, 76
 Some Simple Experiments for First Year Students IX, 28
 Some Thoughts on the Nature of Academic Research in Chemical Engineering X, 2
 Staged Separations VII, 180
 Stanford, ChE Department VI, 102
 Stoichiometry of a City VI, 124
 Storvick, Turk, ChE Educator VIII, 112
 SUNY-Buffalo, ChE Department VII, 112

T

Teaching Experience with Design and Simulation Projects VII, 96
 Teaching Plant Design to Chemical Engineers VIII, 134
 Teaching Undergraduate Mass and Energy Balances 1972+ VIII, 82
 Technology Assessment VII, 184
 Technology Education, ChE VI, 62
 Technological Forecasting IX, 184
 Temperature Approach in Counter-Flow Heat Exchangers X, 36
 Test to Measure the Ability of ChE Seniors in the Practical Application of ChE Principles VIII, 16
 Texaco-Yale Student Consulting Program, The IX, 62
 Texas, ChE Department VII, 8
 Theory of Diffusion and Reaction—A Chemical Engineering Symphony, The VIII, 20
 Thermodynam, A Mnemonic Octahedron of Thermodynamics, The VI, 30
 This Is a Log Table?—1.25 X, 198
 Thoughts About Our First Graduate Courses in Momentum, Energy, and Mass Transfer VI, 174
 Today We Will Hear from the ChE Department VI, 118

Too Much Chemical Engineering Research and Teaching Is Dull, Dull, Dull IX, 52
 Toor, Herb, ChE Educator VIII, 56
 Training of Foreign Graduate Students—Problems and Solutions VII, 200
 Transients in Plug Flow Systems IX, 120
 Trends in Engineering Accreditation—Will the M.S. Become the First Professional Degree? VII, 194
 Tubular Flow of Pseudoplastic Fluids IX, 80
 Turbulent Transfer Processes VI, 128

U

Undergraduate ChE Laboratory, The VII, 122
 Undergraduate Curricula in Chemical Engineering (1969-70) VI, 23
 Undergraduate Curricula in Chemical Engineering (1970-71) VI, 25
 Undergraduate Education: Patterns Today—Extrapolation Tomorrow, ChE VI, 36
 Use of a Continuous System Simulation Language in Chemical Reaction Engineering IX, 133
 Use of Flowsheet Simulation Programs in Teaching Chemical Engineering Design VIII, 124
 Use of FLOWTRAN Simulation in Education X, 90

W

Wastewater Engineering for Chemical Engineers VIII, 184
 Waterloo, ChE Department IX, 4
 Waterloo Program for High Schools VIII, 44
 West Virginia, ChE Department IX, 110
 Whitaker, Steve, ChE Educator VII, 4
 Worcester Polytechnic, ChE Department X, 70

SUBJECT INDEX

A

Accreditation VI, 149
 Administration IX, 180
 Analog Simulation VII, 33; VIII, 94; IX, 88
 Analysis VII, 38, 117; VIII, 176; X, 134
 Applied Surface Chemistry VI, 171

B

Beckmall, Bob, Educator VII, 56
 Bernouli, Equation VIII, 126
 Biochemical Engineering VII, 188; VII, 76; VIII, 188; X, 162
 Biomedical Engineering VI, 162; VII, 76
 Biotechnology IX, 40

Book Reviews

Analysis-VII, 110; Chemistry-VI, 35; Control-IX, 139; Dynamics-VII, 208; Economics-IX, 143; Electrocatalysis-VII, 55; General-VII, 209; Kinetics and Reactors-VIII, 102; Mathematical Methods-IX, 99; X, 124; Polymers-VI, 127; VII, 54; Simulation-VII, 28; Synthesis-VIII,

146; Thermodynamics-VI, 60; VIII, 41; X, 125; Transport Phenomena-VI, 188; Unit Operations-VII, 208; IX, 201, 183; X, 5

C

Carberry, James J., Educator VIII, 2
Cardiopulmonary Simulation — X, 28
Career Guidance, ChE — VI, 110, 111, 114, 122
Catalysis, General-VII, 22; VIII, 172; IX, 138; Enzyme-IX, 188; Heterogeneous-VII, 16; IX, 124, 158
ChE Departments, General-VI, 118; IX, 194; X, 140; Illinois, Urbana-X, 6; Iowa State-X, 108; Loughborough VI, 191; Michigan-VII, 60; Michigan State-VIII, 58; Montana State-VI, 8; Newark-IX, 56; Ohio State-VIII, 106; Princeton-VI, 56; Stanford-VI, 102; SUNY, Buffalo-VII, 112; Texas-VII, 8; West Virginia-IX, 110; Waterloo-IX, 4; Worcester Polytechnic-X, 70
Combustion — X, 40
Computation Methods — VII, 80; VIII, 48
Consulting Program — IX, 62
Corrosion Control — VII, 164
Curricula, Undergrad., ChE — VI, 23, 25, 36; VII, 18; IX, 84

D

Design Laboratory — VII, 129; VIII, 116
Digital Computation — VI, 80; IX, 166
Digital Simulation — VIII, 124; IX, 133; X, 23, 90
Dodge, Barnett F., ChE
Pioneer — VI, 150
Douglas, James, Educator — X, 112

E

Economics, Process — VII, 172
Education, ChE — VI, 40, 50, 92, 132; VIII, 12; X, 80
Education and Accreditation — VI, 49
Educator, ChE — VI, 4, 54, 106; VII, 4, 56, 106; VIII, 2, 56, 112; IX, 2, 76, 106; X, 14, 56, 112
Electrochemical Engineering — X, 158
Energy Engineering — VIII, 200
Entrepreneurship — VI, 181; X, 188
Enzyme and Biochemical Engineering — VIII, 188
Equation Analysis — X, 114

F

Fluid Flow — VII, 132; VIII, 138; IX, 10, 80, 120
Finlayson, Bruce, Educator — IX, 2
Foreign Graduate Students — VII, 200

Foreign Language, Ph.D. — VI, 88
Freshman Engineering — VII, 14; IX, 28, 32; X, 130

G

Graduate ChE Education — VII, 84, 87, 89, 92
Graduate Research — VI, 194; IX, 192
Graduate School — VII, 158

H

Happel, John, Educator — VI, 4
Heat Transfer — VI, 154; X, 36
Horn, Fritz, Educator — VI, 54

I

Interfacial Phenomena — VIII, 32

J

Jackson, Julius L., In
Memoriam — IX, 31

K

Kinetics, Chemical — VI, 134; VII, 161; VIII, 28

L

Laboratory, General-VII, 122; VIII, 74, 98; IX, 8, 22; Design-VII, 129; VIII, 116; Unit Operations-VII, 142, 144; Reactors-VII, 148
Letters, General-VII, 54; X, 16; Chemi Project-X, 17; Grading-VI, 148; X, 154; Quality-VII, 156; X, 16
Littlejohn, C. E., In
Memoriam — IX, 150

M

Mass and Energy Balances — VIII, 82
Mass Transfer — VI, 128; VII, 146; VIII, 20, 204; X, 33
Master's Degree, ChE — VII, 194, 198
Memoriam — IX, 150; X, 59, 107
Microbial Growth — IX, 68
Modeling — VI, 166

O

O'Connell, John P. Educator — X, 14
Organic, Physical Chemistry — VI, 143

P

Pings, Neal, Educator — VII, 106
Pollution — VIII, 184; IX, 128, 170; X, 176
Polymers, Processing-VI, 74; VII, 176; Programs-VII, 30; X, 44; Science-VII, 174; VIII, 194; X, 184
Prausnitz, John, Educator — X, 56
Process Control-VII, 136; VIII, 168; IX, 162; Analog-VII, 40; Digital-VII, 168; VIII, 162; X, 168

Process Design, Complex-X, 136; Costing-VIII, 120, 130; Freshman-IX, 32; X, 130; Laboratory-VII, 129; VIII, 116; Teaching-VI, 178; VIII, 72, 96; VIII, 134

Process Economics — VII, 172
Process Synthesis — VII, 44; X, 134
Proctorial System — VI, 78; X, 76
Professional Engineering — VI, 36, 181; VII, 66; VIII, 66, 142; X, 94, 126

R

Reactor Laboratory — VII, 148
Reactors — VIII, 90; IX, 138; X, 18, 74, 146
Reid, Bob, Educator — IX, 106
Research, ChE — VI, 83; IX, 52; X, 2
Research, Graduate — VI, 194; IX, 192
Rheology — VI, 14
Rutherford, Aris — IX, 118, 119

S

Seagrave, Dick, Educator — VI, 106
Senior Test, ChE — VIII, 16
Separations — VI, 28; VII, 180; IX, 174; X, 84
SI Units — X, 195
Simulation, Digital — VIII, 124; IX, 133; X, 23, 90
Sliepcevich, Cheddy, Educator IX, 76
Stoichiometry — VI, 124
Storvick, Turk, Educator — VIII, 112
Study Program, Foreign-VIII, 78; High School-VIII, 44; Paper and Pulp-IX, 145; Special-VI, 45
Surface Chemistry, Applied — VI, 171

T

Technology-VI, 70; VII, 184; VIII, 164; IX, 184; ChE-VI, 62, 66
Thermodynamics, General-VIII, 180; IX, 115, 152; Entropy-VIII, 149; Equilibrium-VI, 139, 158; VIII, 70; Molecular, VIII, 203; X, 60; Thermodynam-VI, 30
Thermometry — IX, 102
Toor, Herb, Educator — VIII, 56
Transport Phenomena, General-VI, 174; Bernoulli Equation-VII, 126; Fluid Flow-VII, 132; VIII, 138; IX, 10, 80, 120; Heat Transfer-VI, 154; X, 36; Mass Transfer-VI, 128; VII, 146; VIII, 20, 204; X, 33, 190

U

Unit Operations Laboratory — VII, 142, 144

W

Whitaker, Steve, Educator — VII, 4

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I. G. Dalla Lana, Ph.D. (Minnesota): Kinetics, Heterogeneous Catalysis.

D. G. Fisher, Ph.D. (Michigan): Process Dynamics and Control, Real-Time Computer Applications, Process Design.

J. H. Masliyah, Ph.D. (Brit. Columbia): Transport Phenomena, Numerical Analysis, In situ Recovery of Oil Sands.

A. E. Mather, Ph.D. (Michigan): Phase Equilibria, Fluid Properties at High Pressures, Thermodynamics.

W. Nader, Dr. Phil. (Vienna): Heat Transfer, Air Pollution, Transport Phenomena in Porous Media, Applied Mathematics.

F. D. Otto, (Chairman), Ph.D. (Michigan): Mass Transfer, Computer Design of Separation Processes, Environmental Engineering.

D. Quon, (Associate Dean), Sc.D. (M.I.T.): Applied Mathematics, Optimization, Statistical Decision Theory.

D. B. Robinson, Ph.D. (Michigan): Thermal and Volumetric Properties of Fluids, Phase Equilibria, Thermodynamics.

J. T. Ryan, Ph.D. (Missouri): Process Economics, Energy Economics and Supply.

D. E. Seborg, Ph.D. (Princeton): Process Control, Computer Control, Process Identification

F. A. Seyer, Ph.D. (Delaware): Turbulent Flow, Rheology of Complex Fluids.

S. E. Wanke, Ph.D. (California-Davis): Catalysis, Kinetics.

R. K. Wood, Ph.D. (Northwestern): Process Dynamics and Identification, Control of Distillation Columns.

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THE FACULTY AND THEIR RESEARCH INTERESTS ARE:

WILLIAM P. COSART, Assoc. Professor
Ph.D. Oregon State University, 1973
Transpiration Cooling, Heat Transfer in Biological Systems, Blood Processing

JOSEPH F. GROSS, Professor and Head
Ph.D., Purdue University, 1956
Boundary Layer Theory, Pharmacokinetics, Fluid Mechanics and Mass Transfer in The Microcirculation, Biorheology

JOST O.L. WENDT, Assoc. Professor
Ph.D., Johns Hopkins University, 1968
Combustion Generated Air Pollution, Nitrogen and Sulfur Oxide Abatement, Chemical Kinetics, Thermodynamics Interfacial Phenomena

RICHARD D. WILLIAMS, Assoc. Professor
Ph.D., Princeton University, 1972
Catalysis, Chemical Reactor Engineering, Energy and Environmental Problems, Kinetics of Heterogenous Reaction—Applications to the Minerals Industry.

DON H. WHITE, Professor
Ph.D., Iowa State University, 1949
Polymers Fundamentals and Processes, Solar Energy, Microbial and Enzymatic Processes

ALAN D. RANDOLPH, Professor
Ph.D., Iowa State University, 1962
Simulation and Design of Crystallization Processes, Nucleation Phenomena, Particulate Processes, Explosives Initiation Mechanisms

THOMAS R. REHM, Professor
Ph.D., University of Washington, 1960
Mass Transfer, Process Instrumentation, Packed Column Distillation, Applied Design

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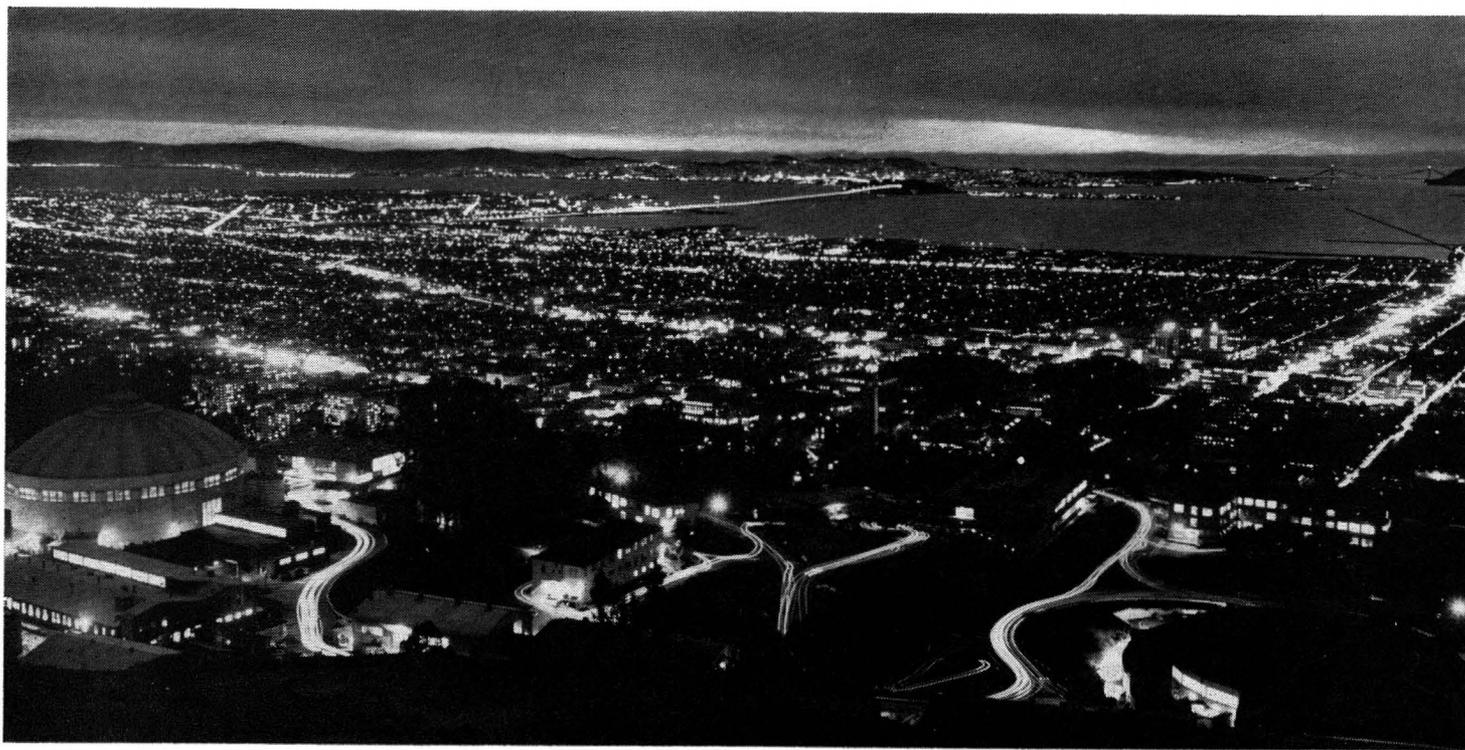
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Ph.D. (1954), University of Illinois
Aerosol chemistry and physics; air pollution; biomedical engineering; interfacial transfer; diffusion and membrane transport.

GEORGE R. GAVALAS, Professor
Ph.D. (1964), University of Minnesota
Applied kinetics and catalysis; process control and optimization; coal gasification.

L. GARY LEAL, Associate Professor
Ph.D. (1969), Stanford University
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Vice-Provost, and Dean of Graduate Studies
Ph.D. (1955), California Institute of Technology
Liquid state physics and chemistry; statistical mechanics.

JOHN H. SEINFELD, Professor,
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Ph.D. (1967), Princeton University
Control and estimation theory; air pollution.

FRED H. SHAIR, Professor
Ph.D. (1963), University of California, Berkeley
Plasma chemistry and physics; tracer studies of various environmental problems.

NICHOLAS W. TSCHOEGL, Professor
Ph.D. (1958), University of New South Wales
Mechanical properties of polymeric materials; theory of viscoelastic behavior; structure-property relations in polymers.

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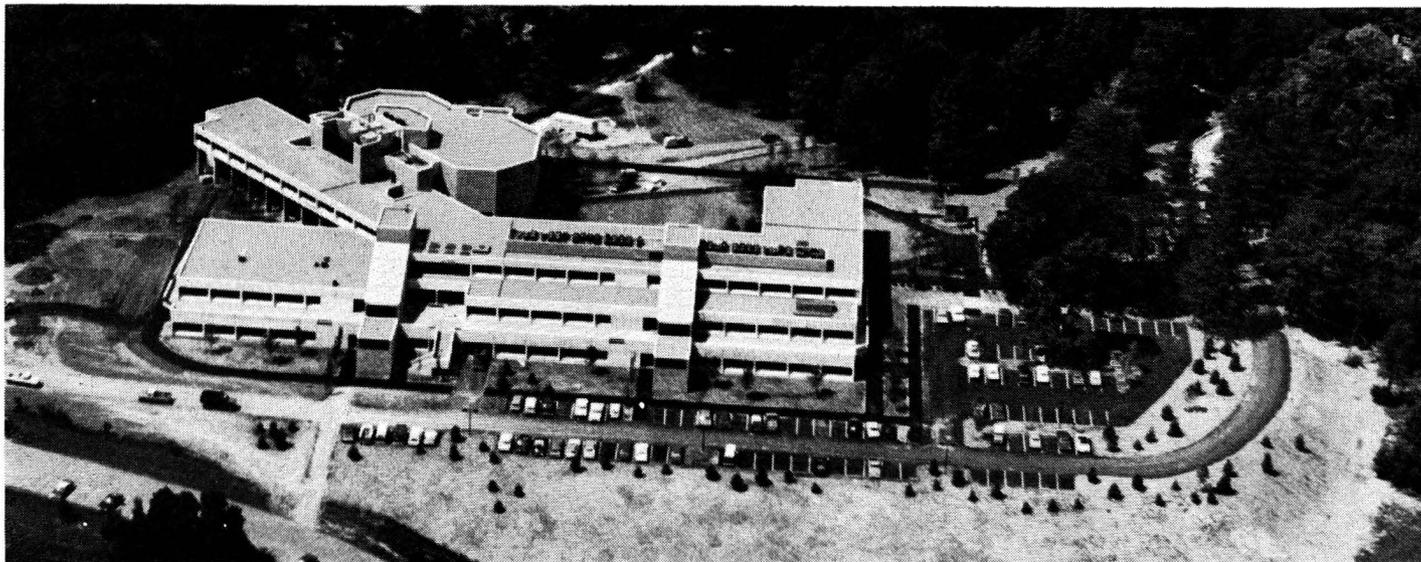
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D-T. CHIN—Assoc. Prof. (Ph.D., 1969, University of Pennsylvania) Electrochemical engineering, transport phenomena, waste treatment and resource recovery, energy conversion, corrosion.

R. COLE—Assoc. Prof. (Ph.D., 1966, Clarkson College of Technology) Boiling heat transfer, bubble dynamics, boiling nucleation, holographic interferometry.

D. O. COONEY—Assoc. Prof. (Ph.D., 1966, University of Wisconsin) Mass transfer in fixed beds, biomedical engineering, pharmacokinetics.

E. J. DAVIS—Prof. (Ph. D., 1960, University of Washington) Heat transfer and fluid mechanics associated with two-phase flow, convective diffusion, aerosol physics, transport phenomena, mathematical modeling.

M. DONAHUE—Asst. Prof. (Ph.D., 1976, University of California, Berkeley) Thermodynamics and phase equilibria.

J. ESTRIN—Prof. (Ph.D., 1960, Columbia University) Nucleation phenomena, crystallization, phase change processes, analysis of energy consuming processes.

J. L. KATZ—Prof. (Ph.D., 1963, University of Chicago) Homogeneous nucleation of vapors, homogeneous boiling, heterogeneous nucleation, aerosols, nucleation of voids in metals, chemical nucleation, thermal conductivity of gases.

R. J. NUNGE—Prof., Dean of the Graduate School and Director, Division of Research. (Ph.D., 1965, Syracuse University) Transport phenomena, multistream forced convection transport processes, structure of pulsating turbulent flow, flow through porous media, atmospheric transport processes.

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P. C. SUKANEK—Asst. Prof. (Ph.D., 1972, University of Massachusetts) Rheology, polymer degradation, continuum mechanics.

T. J. WARD—Assoc. Prof. (Ph.D., 1959, Rensselaer Polytechnic Institute) Process control, nuclear engineering, ceramic materials.

G. R. YOUNGQUIST—Prof. (Ph.D., 1962, University of Illinois) Adsorption, crystallization, diffusion and flow in porous media, waste conversion processes.

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Faculty Members and Research Interests

George G. Cocks, Ph.D. (Cornell): light and electron microscopy, properties of materials, solid-state chemistry, crystallography.

Robert K. Finn, Ph.D. (Minnesota): waste treatment, agitation and aeration, microbial kinetics, enzyme purification.

Keith E. Gubbins, Ph.D. (London): transport properties and thermodynamics of liquids.

Peter Harriott, Sc.D. (M.I.T.): kinetics and catalysis, process control, diffusion in membranes and porous solids.

Robert P. Merrill, Sc.D. (M.I.T.): gas-solid chemical reactions, adsorption and catalysis, chemical kinetics, reactor design.

Ferdinand Rodriguez, Ph.D. (Cornell): polymerization, properties of polymer systems.

George F. Scheele, Ph.D. (Illinois): hydrodynamic stability, coalescence, fluid mechanics of liquid drops and jets.

Michael L. Shuler, Ph.D. (Minnesota): biochemical engineering, novel food sources, plant cells, biological reactors.

Julian C. Smith, Chem.E. (Cornell): conductive transfer processes, heat transfer, mixing, mechanical separations.

James F. Stevenson, Ph.D. (Wisconsin): transport phenomena, rheology.

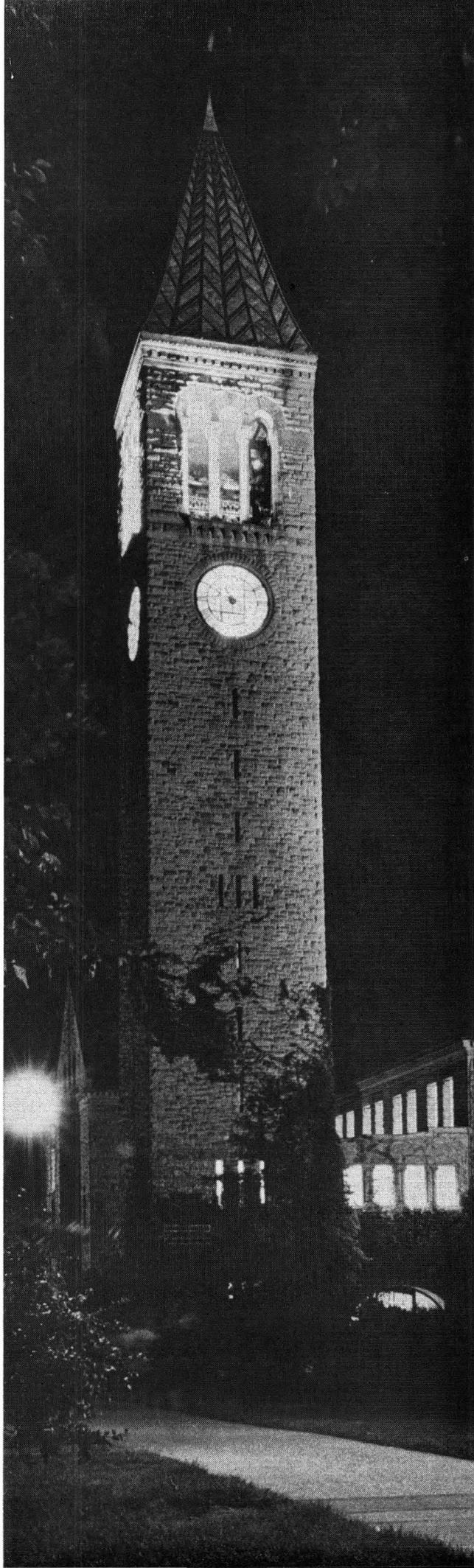
Raymond G. Thorpe, M.Chem.E. (Cornell): phase equilibria, fluid flow, kinetics of polymerization.

Robert L. Von Berg, Sc.D. (M.I.T.): liquid-liquid extraction, reaction kinetics, effect of radiation on chemical reactions, saline-water conversion.

Herbert F. Wiegandt, Ph.D. (Purdue): crystallization, petroleum processing, saline-water conversion, direct contact heat transfer.

Robert York, Sc.D. (M.I.T.): molecular sieves; chemical market analyses; chemical economics; process development, design, and evaluation.

FURTHER INFORMATION. Write to Professor P. Harriott, Olin Hall of Chemical Engineering, Cornell University, Ithaca, New York 14853.



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R. J. Samuels	Polymer science
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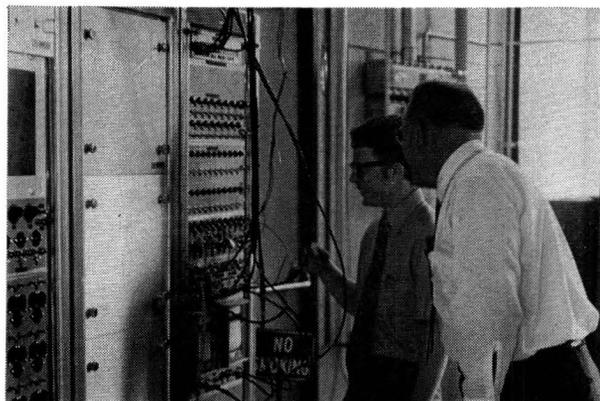
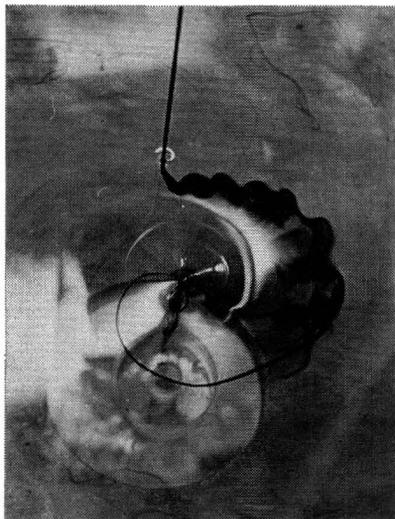
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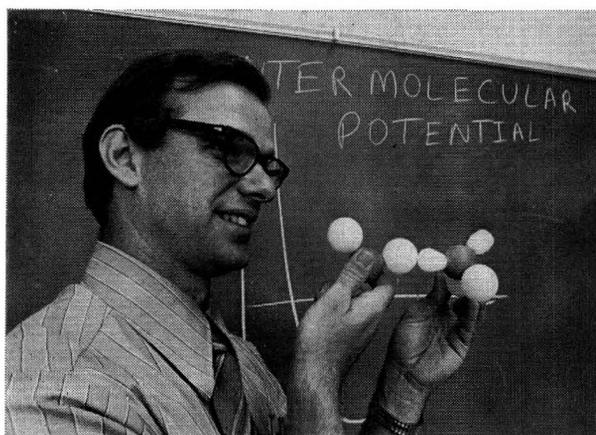
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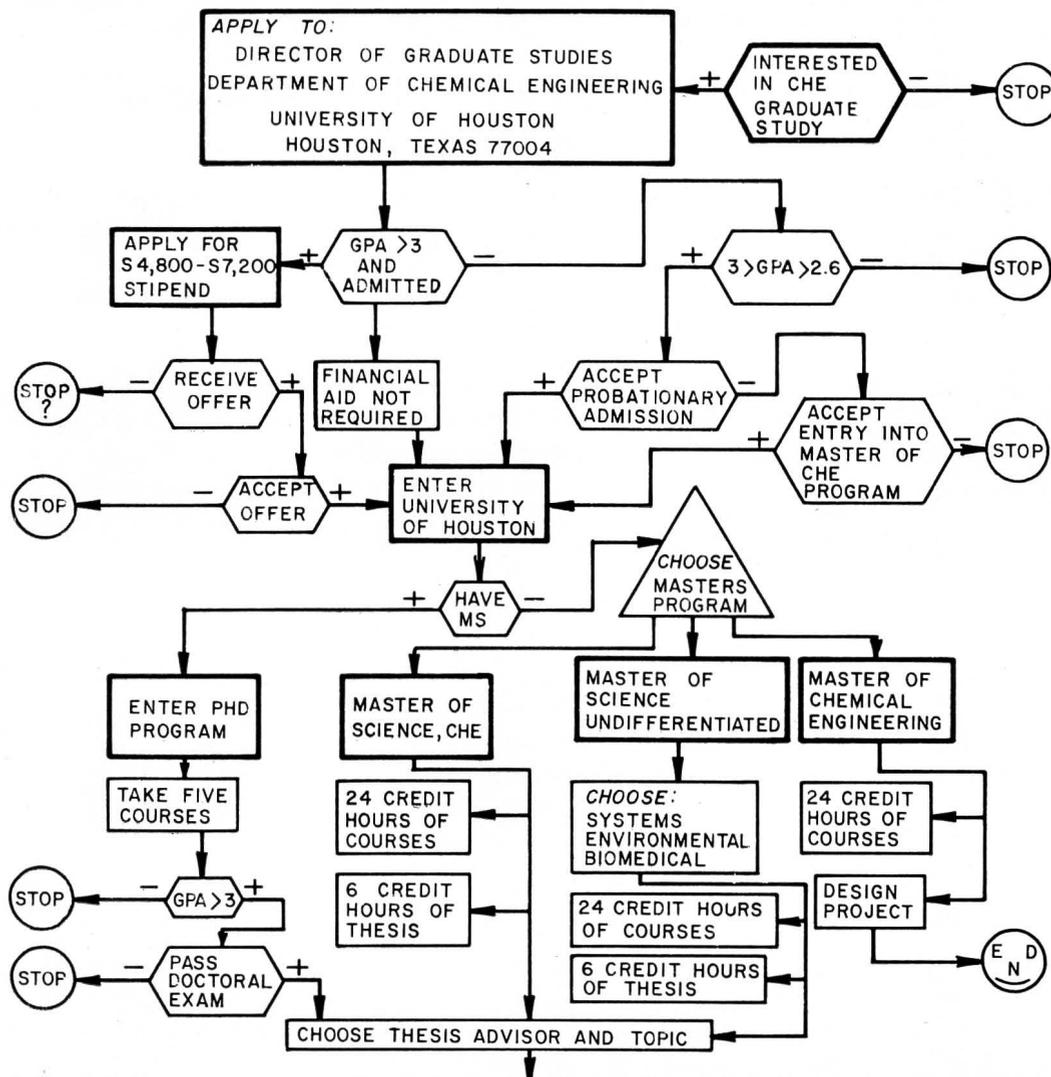
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John H. Kiefer
Ph.D., Cornell University, 1961
Professor

Victor J. Kremesec, Jr.
Ph.D., Northwestern University, 1975
Assistant Professor

G. Ali Mansoori
Ph.D., University of Oklahoma, 1969
Associate Professor

Irving F. Miller
Ph.D., University of Michigan, 1960
Professor

Satish C. Saxena
Ph.D., Calcutta University, 1956
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Ph.D., Illinois Institute of Technology, 1966
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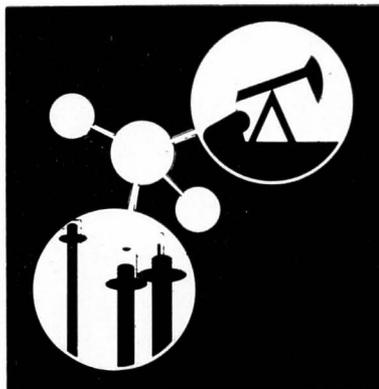
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Prof. D. L. Ulrichson
Dept. of Chem. Engr. & Nuc. Engr.
Iowa State University
Ames, Iowa 50010



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- (e) Process Dynamics and Control; Computer Applications to Process Control—Ds. M. E. Findley, R. C. Waggoner, and R. A. Mollenkamp
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Polymer Engineering
Process Simulation
Surface Phenomena
Separations Techniques
Transport Phenomena

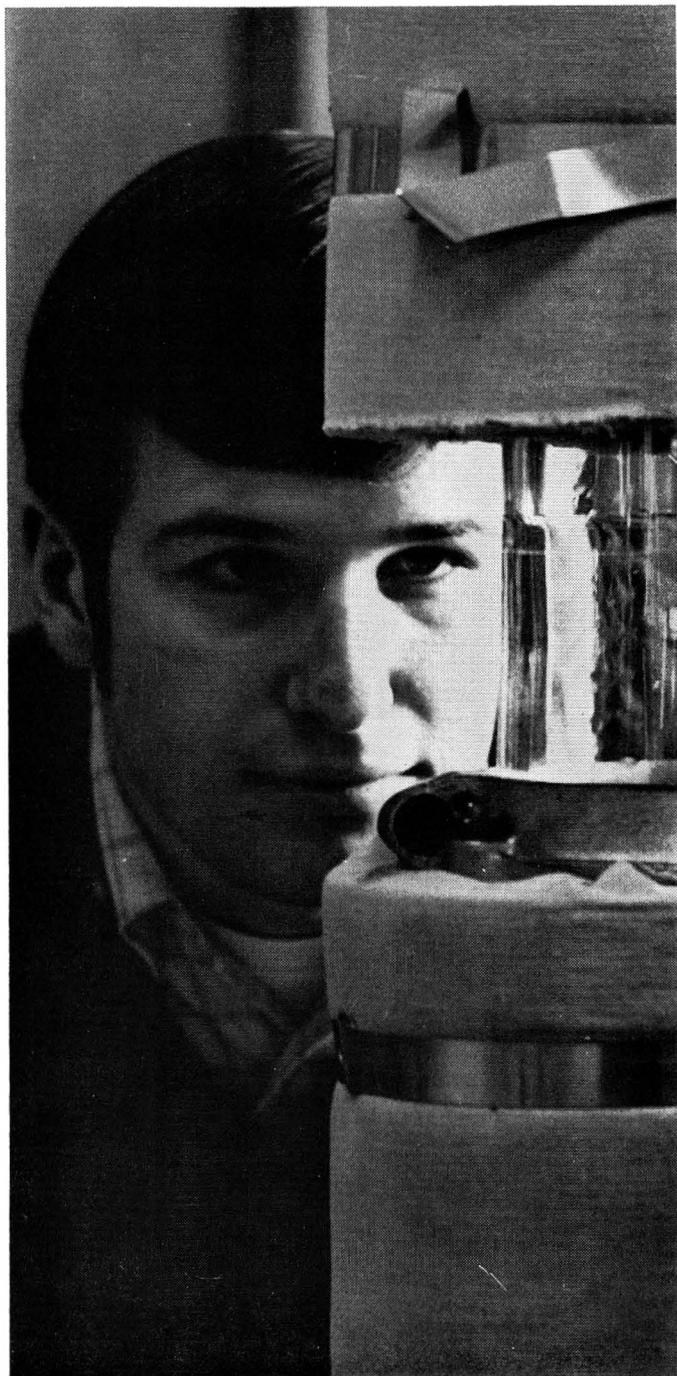
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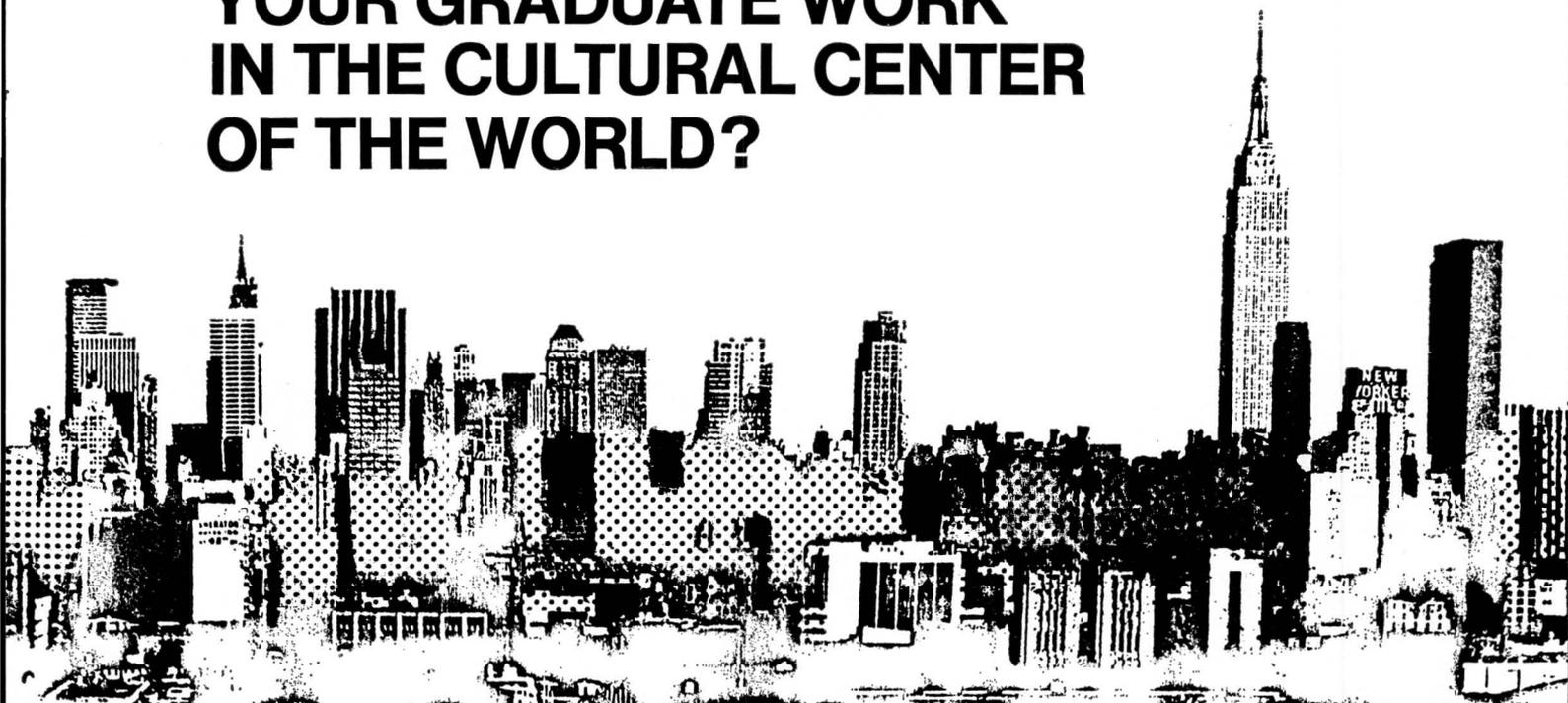
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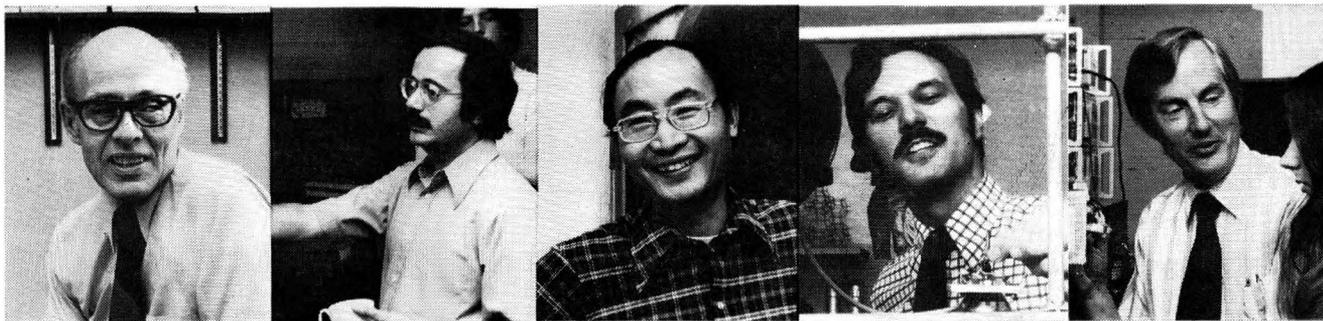
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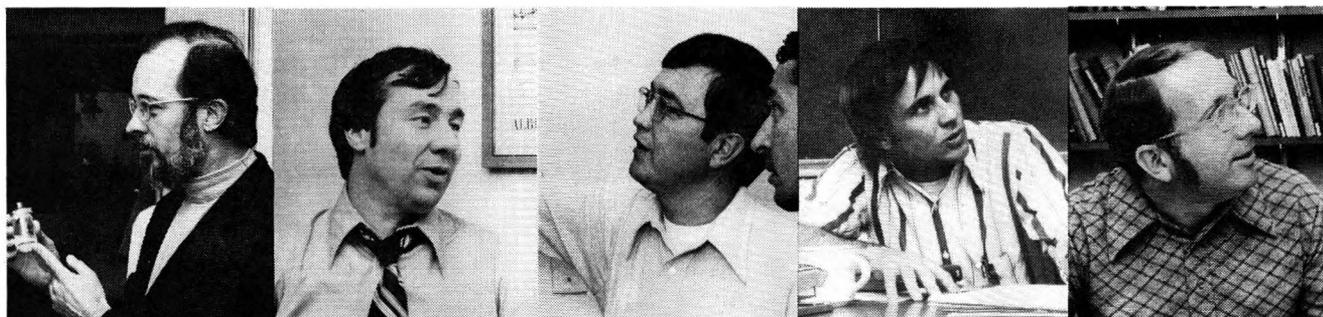
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Chairman
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Rice University
Houston, Texas 77001

Houston

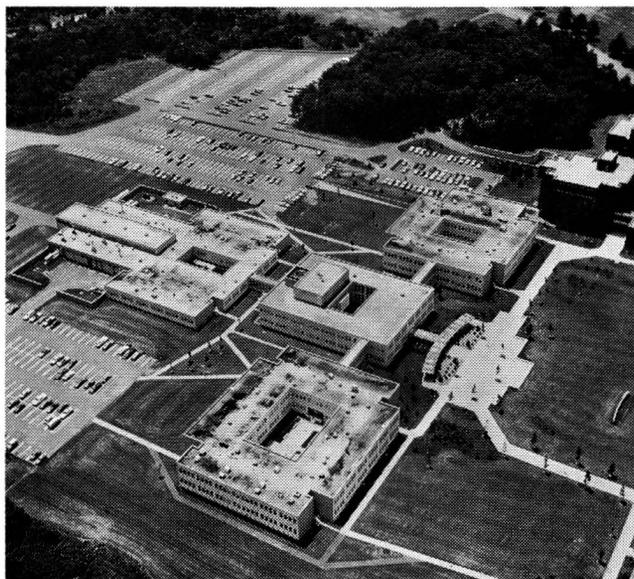
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J. H. Gibbons, Professor, Ph.D., University of Pittsburgh, 1961 (Heat transfer, fluid mechanics)

F. P. Pike, Professor Emeritus, Ph.D., University of Minnesota, 1949 (Mass transfer in liquid-liquid systems, vapor-liquid equilibria)

T. G. Stanford, Assistant Professor, Ph.D., The University of Michigan, 1976 (Chemical reactor engineering, mathematical modeling of chemical systems, process design, thermodynamics)

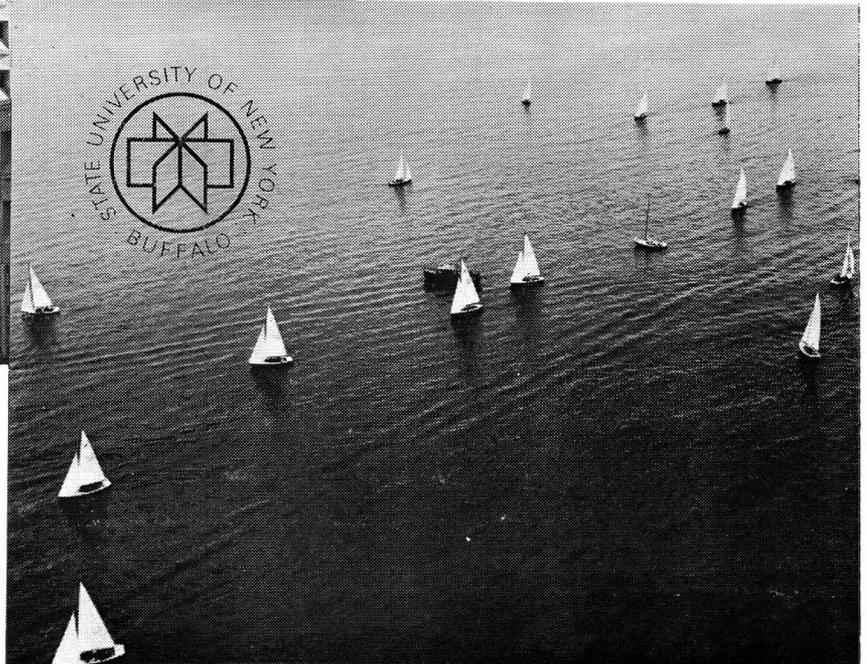
G. B. Tatterson, Assistant Professor, Ph.D., Ohio State University, 1977 (Process control, real time computing, mixing phenomena)

V. Van Brunt, Assistant Professor, Ph.D., University of Tennessee, 1974 (Mass Transfer, Computer Modeling)

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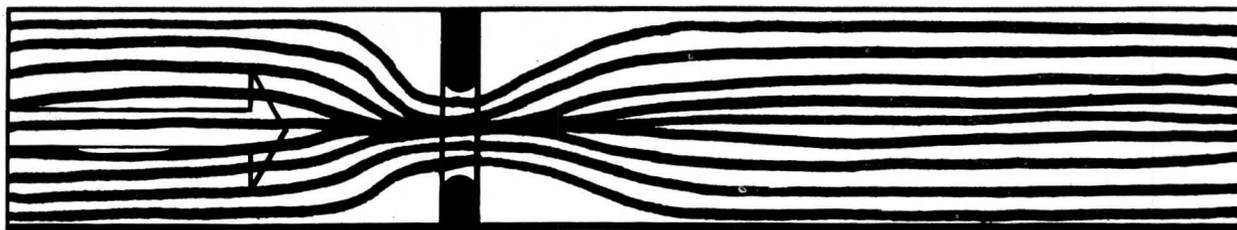
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Fiber and Plastics Processing
Chemical Bioengineering
X-Ray Diffraction, Transmission and
Scanning Electron Microscopy
Solidification, Zone Refining
and Welding
Cryogenic and High Temperature
Calorimetry
Flow and Fracture in Metallic and
Polymeric Systems
Corrosion
Solid State Kinetics

Financial Assistance

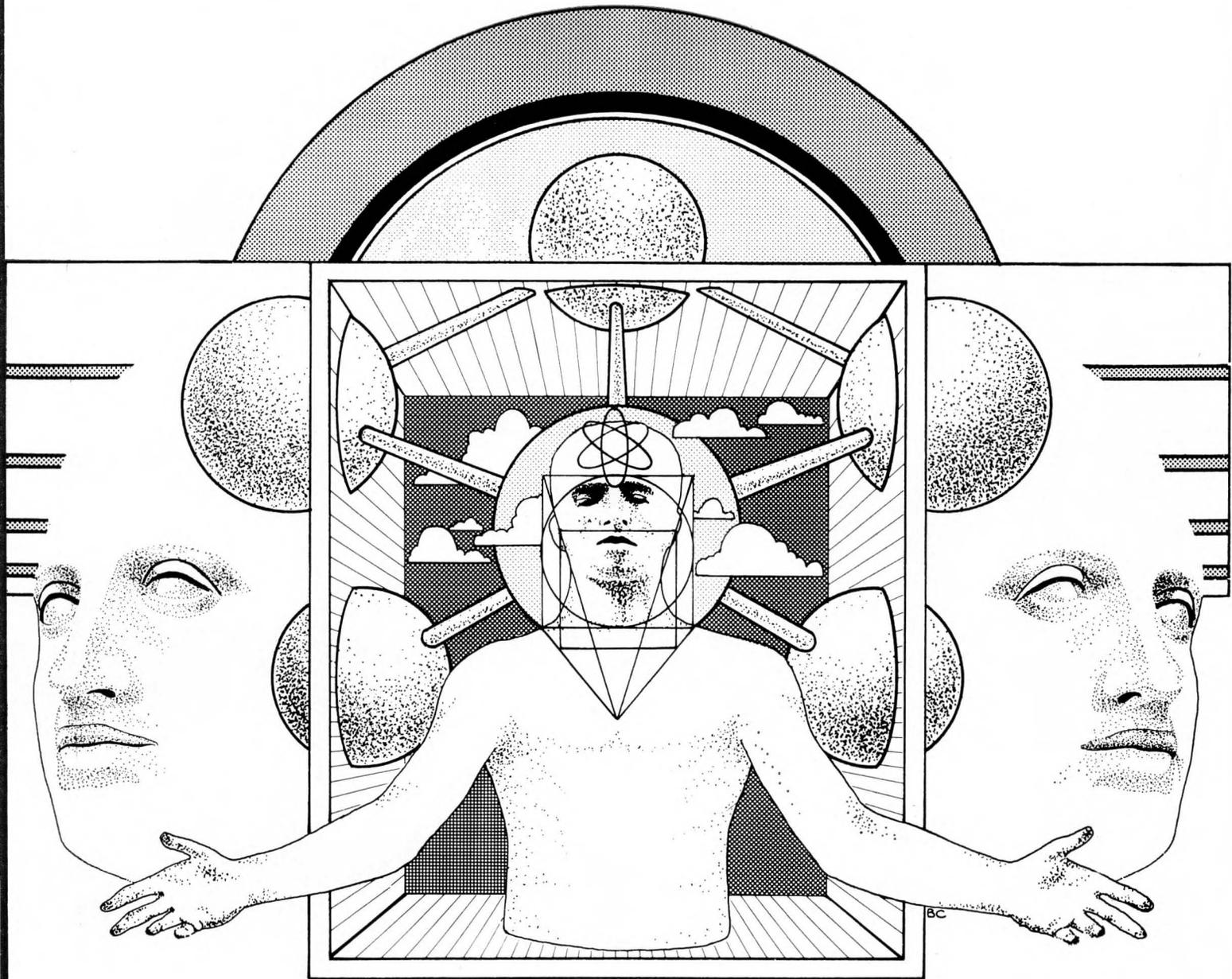
Sources available include graduate teaching assistantships, research assistantships, and industrial fellowships.

Knoxville and Surroundings

With a population near 200,000, Knoxville is the trade and industrial center of East Tennessee. In the Knoxville Auditorium-Coliseum and the University theaters, Broadway plays, musical and dramatic artists, and other entertainment events are regularly scheduled. Knoxville has a number of points of historical interest, a symphony orchestra, two art galleries, and a number of museums. Within an hour's drive are many TVA lakes and mountain streams for water sports, the Great Smoky Mountains National Park with the Gatlinburg tourist area, two state parks, and the atomic energy installations at Oak Ridge, including the Museum of Atomic Energy.

Write

Chemical and Metallurgical Engineering
The University of Tennessee
Knoxville, Tennessee 37916



UNIVERSITY OF TORONTO

TORONTO, CANADA

DEPARTMENT OF CHEMICAL ENGINEERING & APPLIED CHEMISTRY

The Department offers a wide range of research topics for the creative student including:

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- electrochemical engineering and corrosion
- polymer science and engineering
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- process modelling and optimal control
- fluid mechanics and pipeline transportation
- petrochemistry and tar sands development
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- heat, mass and momentum transport
- radiochemistry and radioanalysis
- analytical chemistry and instrumentation
- thermodynamics, kinetics and catalysis
- applied organic chemistry
- environmental engineering
- biomedical engineering
- bioengineering and food synthesis
- pulp and paper chemistry

The Department ranks as one of the largest chemical engineering schools in the world with a total professorial staff of 33 and an enrolment of 160 graduate students. Interdisciplinary research is fostered through joint projects with the Institute for Environmental Studies, the Institute for Biomedical Engineering, the Centre for the Study of Materials, the Systems Building Centre, and the Institute for Aerospace Studies.

Admission to the School of Graduate Studies is based solely on academic standing and availability of space and facilities. A graduate brochure entitled "Graduate Research and Career Development" which describes current research programs is available on request. Adequate financial support in the form of scholarships, fellowships or bursaries is available to qualified students.

For further details write:
Professor R. T. Woodhams, Graduate Secretary
Department of Chemical Engineering
and Applied Chemistry
University of Toronto
Toronto, Ontario
Canada M5S 1A4

West Virginia University



Chemical Engineering

Energy Engineering

Coal Conversion
Potential of Coal Based Energy Complexes
Conversion of Solid Wastes to Low BTU Gas

Environmental Engineering

Purification of Acid Mine Drainage Water
by Reverse Osmosis
Sludge and Emulsion Dewatering
SO₂ Scrubbing
Economic Impact of
Environmental Regulations
River & Lake Modeling

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Separation Processes
Fluidization
Bioengineering
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Utilization of Ultrasonic Energy

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Morgantown, West Virginia 26506



CHEMICAL ENGINEERING

DEGREES: M.S., Ph.D.

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CONTACT: DR. WILLIAM J. HATCHER, JR., HEAD
P. O. BOX G
University, Alabama 35486



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Coordinator of Graduate Studies

- Graduate degrees granted: Master of Science in Chemical Engineering
- For the usual candidate with a B.S. in Chemical Engineering, the equivalent of thirty semester-hours of graduate credit including a thesis is the requirement for graduation. Special programs are arranged for candidates with baccalaureate degrees in the natural sciences.
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R. G. Carbonell	Enzyme Kinetics, Quantum Mechanics
A. P. Jackman:	Process Dynamics, Thermal Pollution
B. J. McCoy:	Molecular Theory, Transport Processes
F. R. McLarnon:	Electrochemistry, Electrochemical Engineering
J. M. Smith:	Water Pollution, Reactor Design
S. Whitaker:	Fluid Mechanics, Interfacial Phenomena

To Receive Applications for Admission and Financial Aid Write To:

Graduate Student Advisor
Department of Chemical Engineering
University of California
Davis, California 95616

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- BIOENGINEERING
- ELECTROCHEMISTRY
- TRANSPORT PHENOMENA
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- ADVANCED ENERGY SOURCES (NUCLEAR, SOLAR, COAL)
- ENVIRONMENTAL ENGINEERING
- MEMBRANE TRANSPORT AND SEPARATION PROCESSES
- OPTIMIZATION AND CONTROL

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PROFESSOR ALAN ULLMAN, ADMISSIONS COMMITTEE
ENERGY AND KINETICS DEPARTMENT
UNIVERSITY OF CALIFORNIA, LOS ANGELES
LOS ANGELES, CALIFORNIA 90024



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A. Edward Profio
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For information, please write to: Department of Chemical and Nuclear Engineering
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Inquiries to: Dr. David B. Greenberg, Head
Dept. of Chemical & Nuclear Engineering (0620)
University of Cincinnati
Cincinnati, Ohio 45221



CLEMSON UNIVERSITY

Chemical Engineering Department

M.S. and Doctoral Programs

THE FACULTY AND THEIR INTERESTS

Alley, F. C., Ph.D., U. North Carolina—Industrial Pollution Control
Barlage, W. B., Ph.D., N. C. State—Transfer Processes in Non-Newtonian Fluids, Interfacial Phenomena
Beard, J. N., Ph.D., L.S.U.—Digital Computer Process Control, Textile Dyeing and Finishing
Beckwith, W. F., Ph.D., Iowa State—Transport Phenomena, Pulp and Paper Processing
Eddie, D. D., Ph.D., U. Virginia—Crystallization, Polymer Processing
Haile, J. M., Ph.D., U. Florida—Statistical Thermodynamics, Computer Simulation of Fluids
Harshman, R. C., Ph.D., Ohio State—Kinetics and Reactor Design, Membrane Processes
Melsheimer, S. S., Ph.D., Tulane—Membrane Transport, Numerical Methods, Process Control
Mullins, J. C., Ph.D., Georgia Tech—Thermodynamics, Adsorption
Talbot, W. H., Ph.D., U. Michigan—Rheology, Fluid Mechanics, Heat Transfer

FINANCIAL ASSISTANCE—Fellowships, Assistantships, Traineeships

Contact:

D. D. Edie, Graduate Coordinator
Department of Chemical Engineering
Clemson University
Clemson, S. C. 29631

COLORADO SCHOOL OF MINES GRADUATE STUDY IN CHEMICAL ENGINEERING

PROGRAM—The Chemical and Petroleum-Refining Engineering Department offers graduate programs leading to M.S., or Ph.D. degrees in chemical engineering. Three semesters will normally be required for the M.S. degree, and three or more years for the Ph.D. degree. These degree programs are flexible in scope, and will be adjusted to meet the needs and desires of each student.

FINANCIAL ASSISTANCE—Both research assistantships and teaching assistantships are available with stipends to \$450 per month plus tuition for the academic year.

LOCATION—The Colorado School of Mines, in Golden, Colorado, is picturesquely situated in the foothills of the Rocky Mountains, 13 miles west of Denver. Most of Colorado's beautiful recreation areas for hiking, camping, or skiing are easily reached from Golden.

LIVING ACCOMODATIONS—Most graduate students, both single and married, prefer to live in private apartments in the Golden-Denver area. For those students desiring to live on campus, the School maintains resident halls for single students and apartments for married students.

the university of connecticut

faculty

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C. O. BENNETT
R. W. COUGHLIN
M. B. CUTLIP
A. T. DiBENEDETTO
G. M. HOWARD
H. E. KLEI
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location — Beautiful setting in rural Northeast Connecticut, convenient to Boston, New York, and Northern New England

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The University of Connecticut
Storrs, Connecticut 06268

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Department of Chemical Engineering
Whitaker Laboratory, Bldg. 5
Bethlehem, Pa. 18015

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Curtis W. Clump	Thermodynamics
Robert W. Coughlin	Energy/Fossil Fuels
Mohamed El-Aasser	Nuclear Technology
Alan S. Foust	Polymer Materials Science
William L. Luyben	Numerical Integration
Anthony J. McHugh	Catalysis
Gary W. Poehlein	Chemical Reactor Engineering
William E. Schiesser	Fermentation and Biochemical Engineering
Leslie H. Sperling	Enzyme Technology
Fred P. Stein	Cryogenics
Leonard A. Wenzel	Process Design
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	Process Dynamics
	Waste Water Treatment
	Air Pollution Control
	Rheology
	Emulsion Polymerization
	Computer Simulation
	Surface Science
	Process Control
	Transport Phenomena
	Kinetics

LSU

Graduate Enrollment — 60

Faculty — 19

- Bioengineering
 - Pollution Control
 - Process Dynamics
 - Computer Control
 - Kinetics and Catalysis
 - Thermodynamics
 - Ecological Modeling
 - Sugar Technology

Write: Chemical Engineering Department
Louisiana State University
Baton Rouge, Louisiana 70803

CHEMICAL ENGINEERING DEPARTMENT



UNIVERSITY OF MARYLAND

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The Department offers a broad program of graduate studies leading to MS and PhD degrees. Specialties available in Biochemical, Environmental Process Analysis and Simulation, Polymers, and Energy-related areas.

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Tuition for the 1976-77 academic year is \$40 per credit hour for Maryland residents and \$85 per credit hour for nonresidents.

**Cost of
Living:**

Board and lodging are available in many private homes and apartments in College Park and vicinity, with recent estimates suggesting that accommodations may cost anywhere from \$100 to \$200 monthly. A list of accommodations is maintained by the University's Housing Bureau.

**The
Community:**

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**Financial
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McMASTER UNIVERSITY

Hamilton, Ontario, Canada
M. ENG. & PH.D. PROGRAMS

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M. H. I. Baird (Ph.D., Cambridge)	Oscillatory Flows, Transport Phenomena
A. Benedek (Ph.D., U. of Washington)	Wastewater Treatment, Novel Separation Techniques
J. L. Brash (Ph.D., Glasgow)	Polymer Chemistry, Use of Polymers in Medicine
C. M. Crowe (Ph.D., Cambridge)	Optimization, Chemical Reaction Engineering, Simulation
I. A. Feuerstein (Ph.D., Massachusetts)	Biological Fluid and Mass Transfer
A. E. Hamielec (Ph.D., Toronto)	Polymer Reactor Engineering, Transport Processes
T. W. Hoffman (Ph.D., McGill)	Heat Transfer, Chemical Reaction Engr., Simulation
J. F. MacGregor (Ph.D., Wisconsin)	Statistical Methods in Process Analysis, Computer Control
K. L. Murphy (Ph.D., Wisconsin)	Wastewater Treatment, Physicochemical Separations
L. W. Shemilt (Ph.D., Toronto)	Mass Transfer, Corrosion
W. J. Snodgrass (Ph.D., U. of N. Carolina, Chapel Hill)	Modelling of Aquatic Systems
J. Vlachopoulos (D.Sc., Washington U.)	Polymer Rheology and Processing, Transport Processes
D. R. Woods (Ph.D., Wisconsin)	Interfacial Phenomena, Particulate Systems
J. D. Wright (Ph.D., Cambridge)	Process Simulation and Control, Computer Control

DETAILS OF FINANCIAL ASSISTANCE AND ANNUAL RESEARCH REPORT AVAILABLE UPON REQUEST

CONTACT: Dr. A. E. Hamielec, Chairman,
Department of Chemical Engineering
Hamilton, Ontario, Canada L8S 4L7



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Chairman of the Graduate Committee
The University of Michigan
Department of Chemical Engineering
Ann Arbor, Michigan 48104

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For more information write:



H. El Khadem, Head
Department of Chemistry and Chemical Engineering
Michigan Technological University
Houghton, Michigan 49931

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- ... as a domain dominated by dismal theoreticians and other weird species?

IF SO

- ... you're wrong on both counts. Our weather is brisk, to be sure, but far from glacial. Our theoreticians are doughty not dismal; and anyway the experimentalists outnumber the theoreticians—nor do they themselves fear theory.

For the unexpurgated truth on graduate work at Minnesota, write:

DIRECTOR OF GRADUATE STUDIES

Department of Chemical Engineering & Materials Science
University of Minnesota, Minneapolis, MN 55455

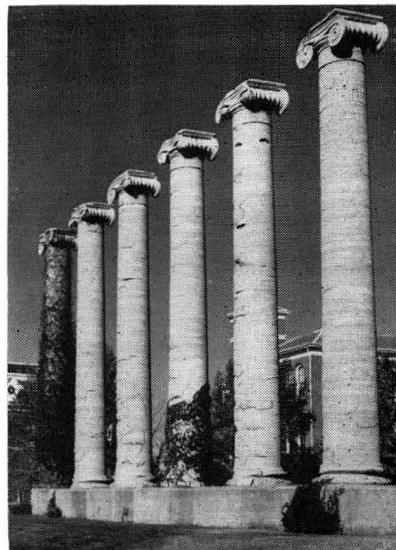
UNIVERSITY OF MISSOURI - COLUMBIA

DEPARTMENT OF CHEMICAL ENGINEERING

Studies Leading to M.S. and Ph D.
Degrees

Research Areas

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- Catalysis
- Energy Sources and Systems
- Environmental Control Engineering
- Heat and Mass Transport Influence by Fields
- Newtonian and Non-Newtonian Fluid Mechanics
- Process Control and Modelling of Processes
- Single-Cell Protein Research
- Thermodynamics and Transport Properties of Gases and Liquids
- Transport in Biological Systems



WRITE: Dr. George W. Preckshot, Chairman, Department of Chemical Engineering, 1030 Engineering Bldg., University of Missouri, Columbia, MO 65201

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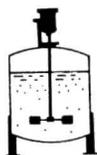
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- Reaction Engineering
- Fluidisation

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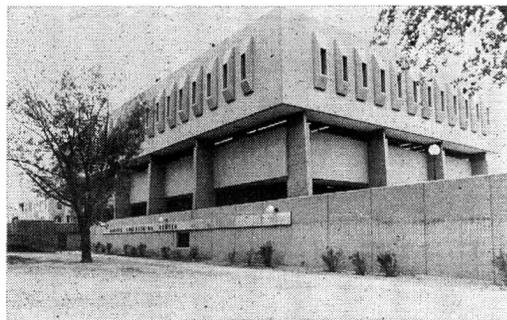
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G. M. Brown	Thermodynamics, Process Simulation
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S. H. Carr	Solid State Properties of Polymers, Biodegradation
W. C. Cohen	Dynamics and Control of Process Systems
B. Crist	Polymers in the Solid State
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W. W. Graessley	Polymer Rheology, Polymer Reaction Engineering
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H. H. Kung	Catalyst Behavior, Properties of Oxide Surfaces
G. G. Lamb	Analysis of Societal Change
R. S. H. Mah	Computer-Aided Process Planning, Design and Analysis
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Financial support is available

For information and application materials, write:

**Professor William F. Stevens, Chairman
Department of Chemical Engineering
Northwestern University
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 - Heat, Mass and Momentum Transfer
 - Nuclear Chemical Engineering
 - Rheology
 - Energy Sources and Conversion
 - Optimization and Advanced Mathematical Methods
 - Biomedical Engineering and Biochemical Engineering
- Process Analysis, Design and Control
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 - Petroleum Reservoir Engineering
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 - Unit Operations
 - Process Dynamics and Simulation

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William B. Russel
Dudley A. Saville
William R. Schowalter
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Energy Conversion & Fusion Reactor Technology
Environmental Studies
Fluid Mechanics & Rheology
Mass & Momentum Transport
Molecular Beams
Polymer Materials Science & Rheology
Process Control & Optimization

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Director of Graduate Studies
Chemical Engineering
Princeton University
Princeton, New Jersey 08540





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H.A. Becker Sc.D (MIT)
D.H. Bone Ph.D (London)
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R.H. Clark Ph.D (Imperial College)
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J. Downie Ph.D (Toronto)
J.E. Ellsworth Ph.D (Princeton)
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- Chemical Reaction Engineering
catalysis
statistical design
polymer studies
- Transport Processes
combustion
fluid mechanics
thermodynamics

Write:

Dr. John Downie
Department of Chemical Engineering
Queen's University
Kingston, Ontario
Canada

FACULTY:

ANDREAS ACRIVOS (Ph.D., 1954, Minnesota)
Fluid Mechanics.

MICHEL BOUDART (Ph.D., 1950, Princeton)
Kinetics & Catalysis.

CURTIS W. FRANK (Ph.D., 1972, Illinois)
Polymer Physics.

GEORGE M. HOMSY (Ph.D., 1969, Illinois)
Fluid Mechanics & Stability.

ROBERT J. MADIX (Ph.D., 1964, U. Cal-Berkeley)
Surface Reactivity.

DAVID M. MASON (Ph.D., 1949, Cal Tech)
Applied Thermodynamics & Chemical Kinetics.

CHANNING R. ROBERTSON (Ph.D., 1969, Stanford)
Bioengineering.

LECTURERS & CONSULTING FACULTY:

RICHARD E. BALZHISER, E.P.R.I., Palo Alto, CA (Ph.D., 1961, Michigan)
Heat Transfer & Thermodynamics.

ALAN S. MICHAELS, Alza Corporation, Palo Alto, CA (Sc.D., 1948, M.I.T.)
Surface, Colloid & Polymer Chemistry.

ROBERT H. SCHWAAR, S.R.I., Menlo Park, CA. (Ph.D., 1956, Princeton)
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AT

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Stanford University
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Environmental Engineering
Rensselaer Polytechnic Institute, Troy, New York
12181.**



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- *Extractive and Process Metallurgy
- *Polymer Science and Engineering
- *Mathematical Analysis and Control
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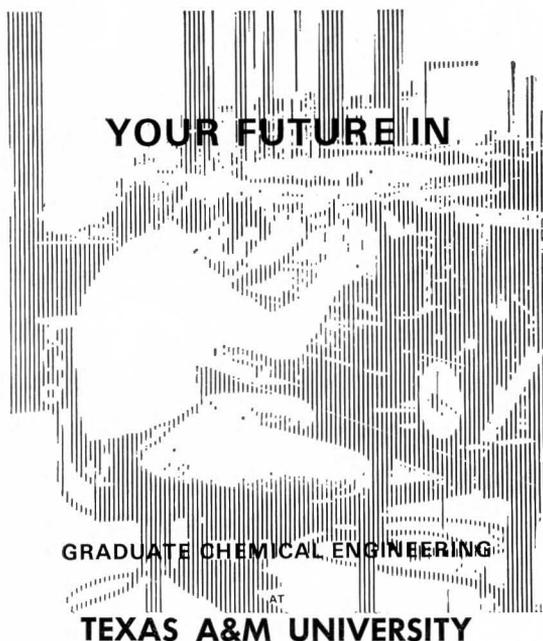
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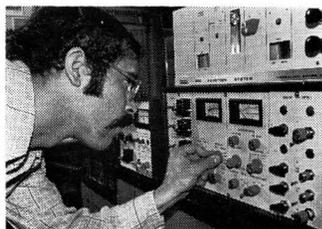
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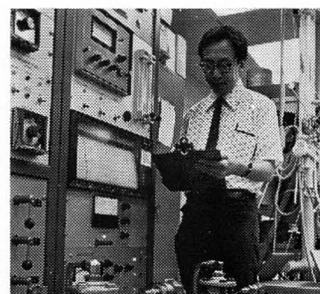
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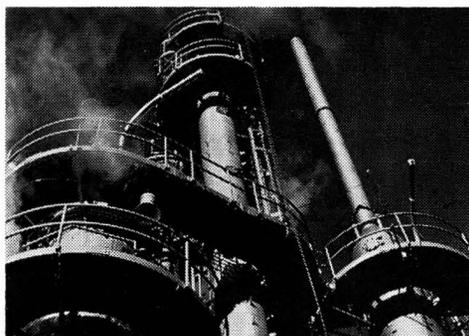
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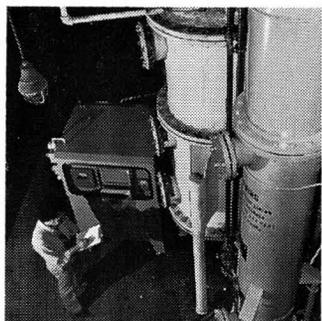
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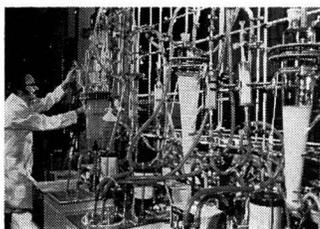
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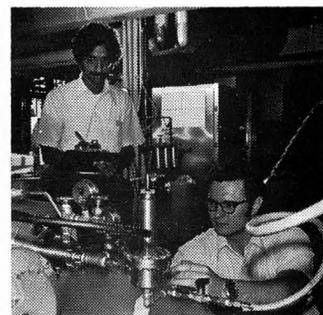
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