CEE

chemical engineering education

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CHEMICAL ENGINEERING DIVISION OF AMERICAN SOCIETY FOR ENGINEERING EDUCATION

Graduate Education Issue

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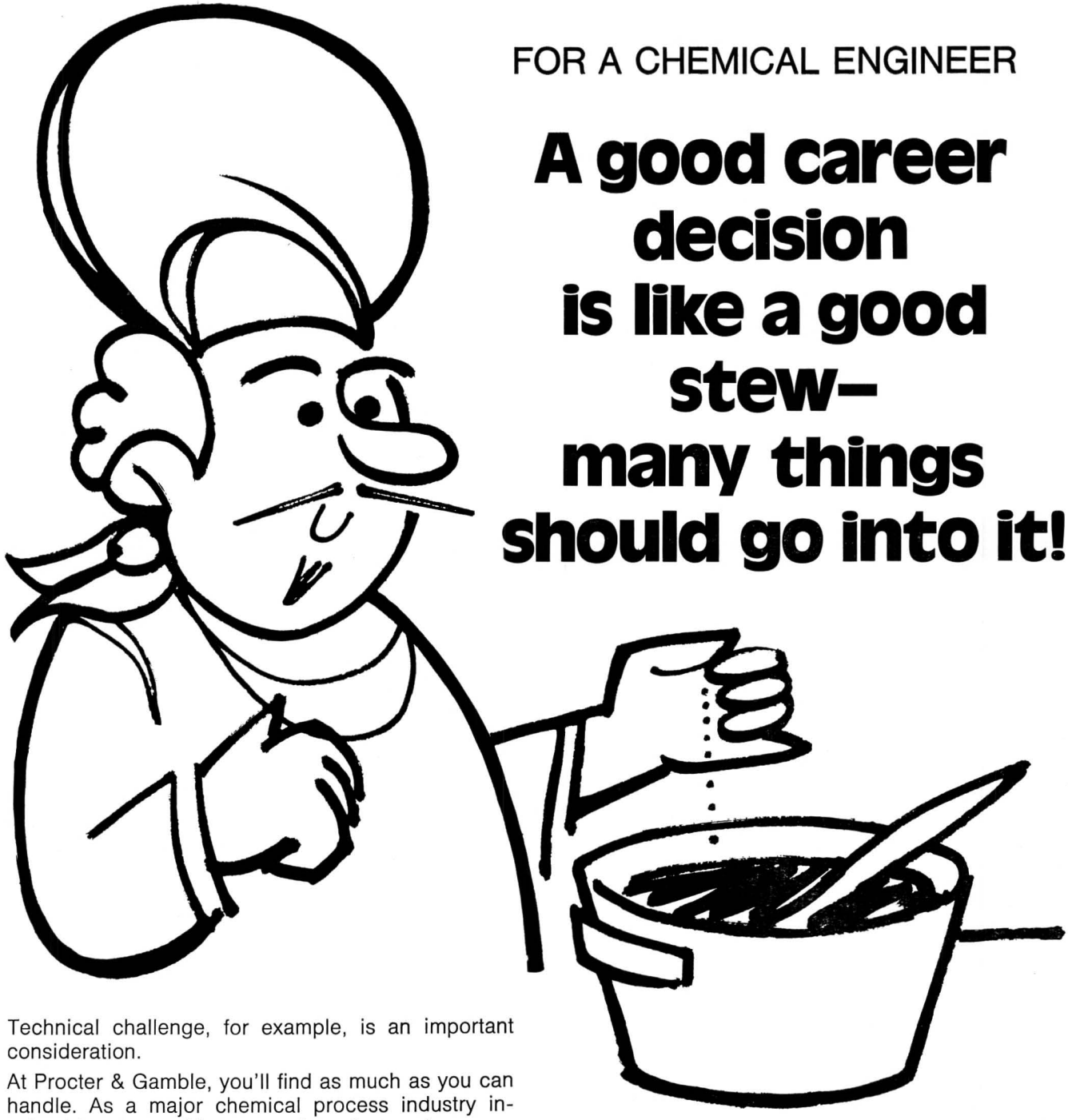

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GRADUATE COURSE ARTICLES

DEPARTMENTS

FEATURES

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ChE letters

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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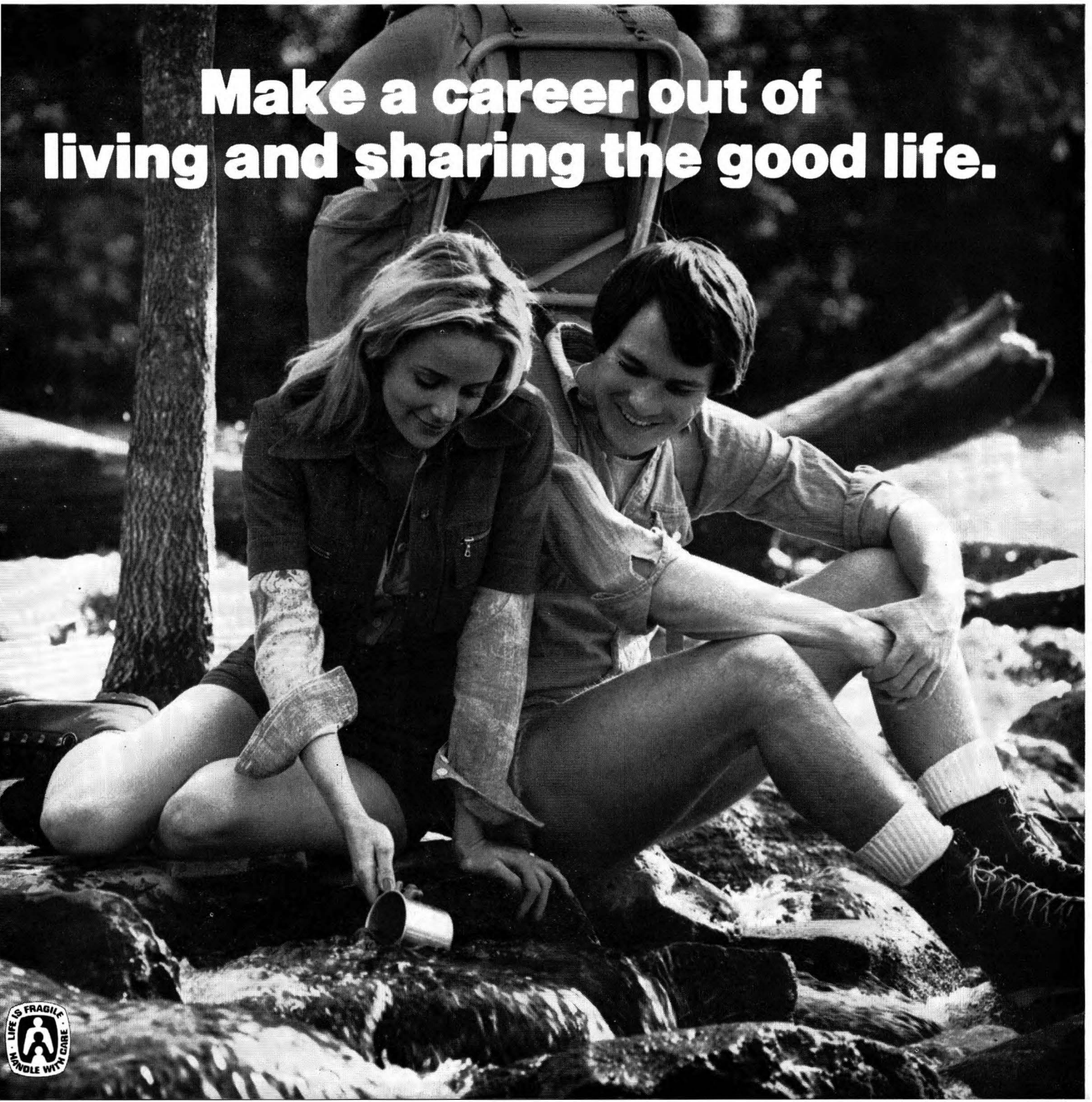

A Course in

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 fur physikalische Chemie at Gottingen. 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. Disciples 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 students gain a fuller sense of the complex relation between process variables and process behavior.

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.

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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1. R. B. MacMullin, J. Electrochem. Soc., *120*, 135C (1973).
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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The development of this course has taken place over a period of time during which the interest and guidance of several colleagues have been most sincerely appreciated. In particular, I am pleased to acknowledge fruitful conversations with Professor Sherlock Swann Jr. (University of Illinois), Charles Tobias, John Newman (both of the University of California at Berkeley), Thomas Chapman (University of Wisconsin), Robert MacMullin (MacMullin Associates), and Manuel Baizer (Monsanto Company).

A Survey Course

BIOCHEMICAL ENGINEERING FUNDAMENTALS

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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 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.

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

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 *á 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 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.

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 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, divertissements 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 (synchonous 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)

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 Interation (lumped, distributed models for cells, floes, 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 Affective $k_l a$ (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 (bath; continuous)
- E. Relationships Between Batch and Continuous Biological Reactors (Example: Reactor modeling and optimization for production of α-Galactosidase by a Monascus sp. mold)

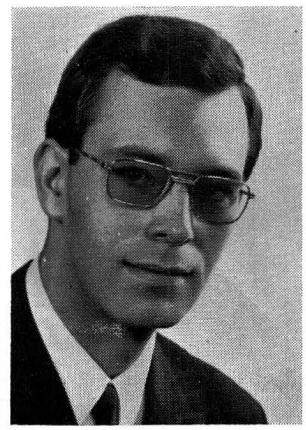
X. BIOLOGICAL REACTORS, SUBSTRATES, AND PRODUCTS I: SINGLE SPECIES APPLICATIONS
- A. Fermentation Technology (medium formulation; aseptic practice; cell harvesting, product recovery)
- B. Product Manufacture by Fermentation (brewing and wine making; oxidative transformations; organic, amino acids; complex molecules: gibberelins, vitamins, antibiotics; undesirable products) (Example: Reaction rates in microbial films; temperature programming for optimal pencillin 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, Mutalism, 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 mutalistic 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)

A Course in

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 C S T R 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

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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Continued on page 174.

A Course in

DISTILLATION DYNAMICS AND CONTROL

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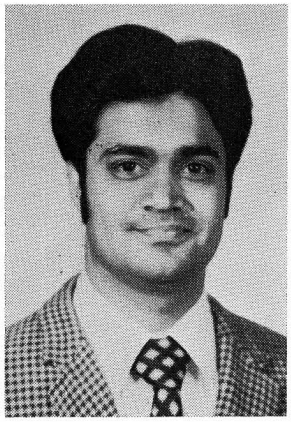
A TYPICAL UNDERGRADUATE curriculum in chemical engineering includes courses in unit operations, process design, and process control. In the first of these, a number of unit operations, e.g., distillation, absorption, extraction, are studied. In distillation, the following topics are usually covered: 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 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.



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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 PhD. 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

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

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

where

Z_F, X_D, X_B = composition of the more volative 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

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

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

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

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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A Course in

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 program 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

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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 Fussion 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, 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.

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.

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.
3. Glasstone, S., and R. H. Lovberg, "Controlled Thermonuclear Reactions," D. Van Nostrand Co., Princeton, New Jersey, 1960.
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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DE KEE: Food Engineering

Continued from page 167.

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ENVIRONMENTAL COURSES

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Pittsburgh, Pennsylvania 15261

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

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.

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 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.

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

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

stadard 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.

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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BOOK REVIEW: Multivariable Computer Control

Continued from page 154

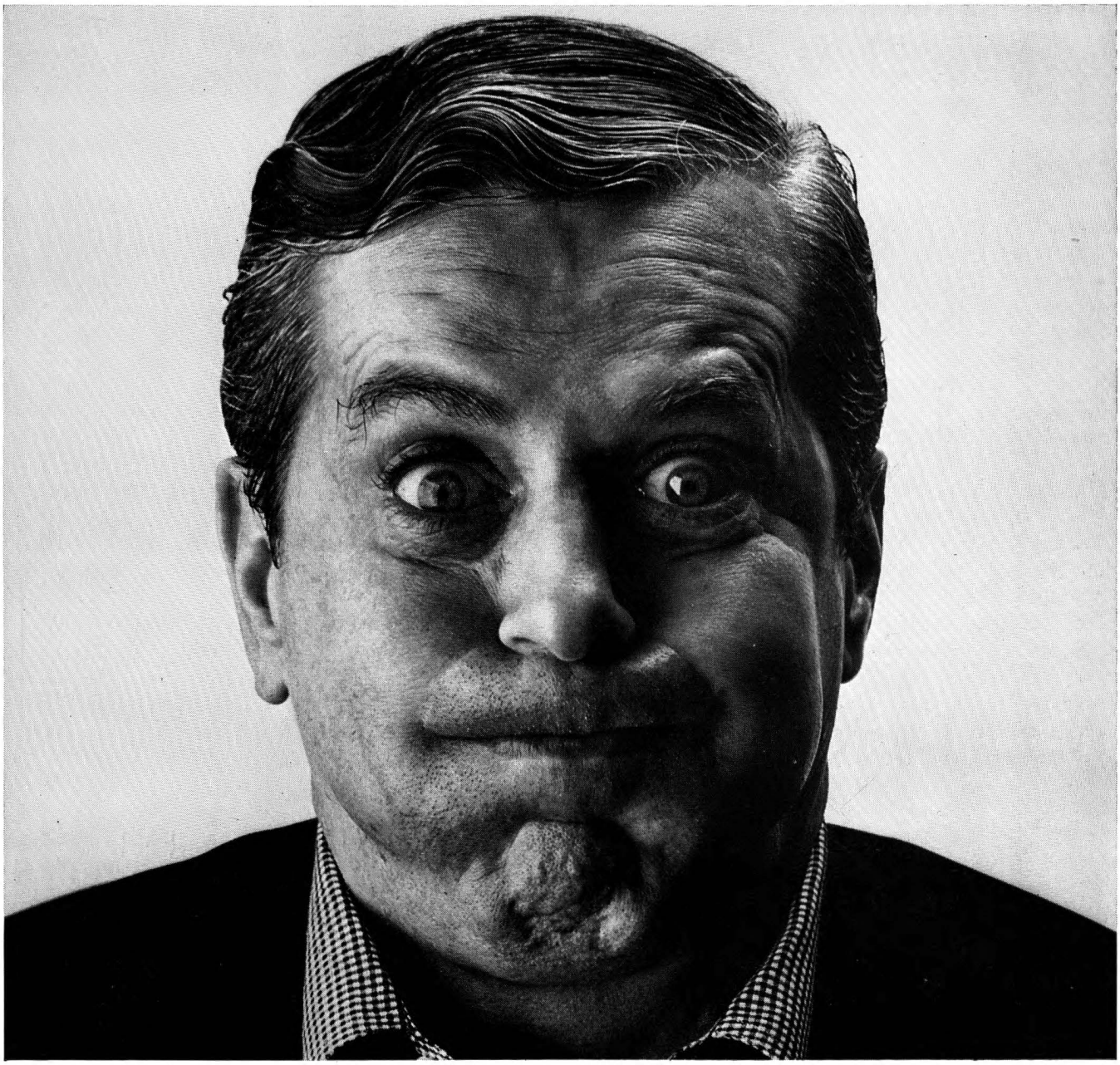
publish these together in a single volume. The result is the present book.

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 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.

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.



Hold your breath for 60 seconds.

Try this little experiment and chances are you'll find the last few seconds unbearable.

That desperate, terrifying sensation is caused by a lack of oxygen and an excess of carbon dioxide.

People with emphysema or other lung diseases know the feeling well. They live with it 24 hours a day.

Oxygen therapy can help many of them. But it can also sentence them to a bleak existence—living in fear, bound to heavy, bulky oxygen tanks.

Union Carbide has developed a portable oxygen system.

We call it the Oxygen Walker.

It's small enough to be carried on a shoulder strap and weighs only 11 pounds full. Yet, incredibly, this handy pack can supply over 1000 liters of oxygen gas—enough for 8 hours or more, depending on individual flow rates.

Taking the Oxygen Walker with them, patients are free to leave their homes. Free to go walking, shopping, fishing... many have even returned to work.

The Oxygen Walker is only one of the things we're doing with oxygen. We supply more of it than anyone else in the country. For steelmaking, hospitals, wastewater treatment and the chemical industry.

But, in a way, the Walker is the most important use of our oxygen. Because to the people who use it, it is the breath of life.

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A Course in

ADSORPTIVE BUBBLE SEPARATION METHODS

ROBERT LEMLICH
University of Cincinnati
Cincinnati, Ohio 45221

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 sublate 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.

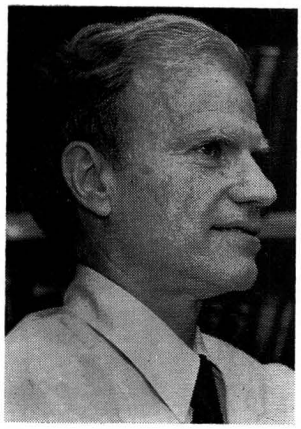
The course begins with an introductory overview of the field. The various adsubble techniques are briefly described and compared. The pervading importance of surface activity and solute surface excess are carefully noted.

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

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

A Course in

INTRODUCTORY POLYMER SCIENCE AND TECHNOLOGY

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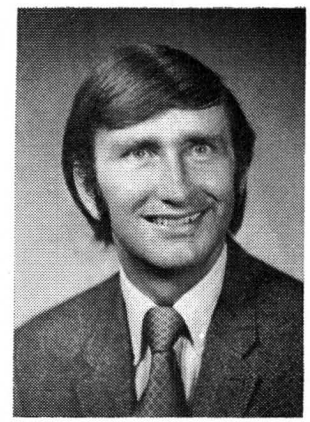
IN THE COURSE OF THIRTY years the polymer industry has grown enormously to the present levels of production comparable to that of steel. It is estimated that 30% of all chemistry and ChE graduates are employed in some field of endeavor involving polymeric materials. In this time period the industry matured 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



J. Koutsky obtained his BS and MS in Chemical Engineering and his PhD in Polymer Science and Engineering (1966) from Case Institute of Technology. He has been at the University of Wisconsin-Madison since 1966. His research interests involve solid-state structure studies of polymers, adhesion of thermosetting polymers and cryogenic recycling of polymer wastes.

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 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:

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

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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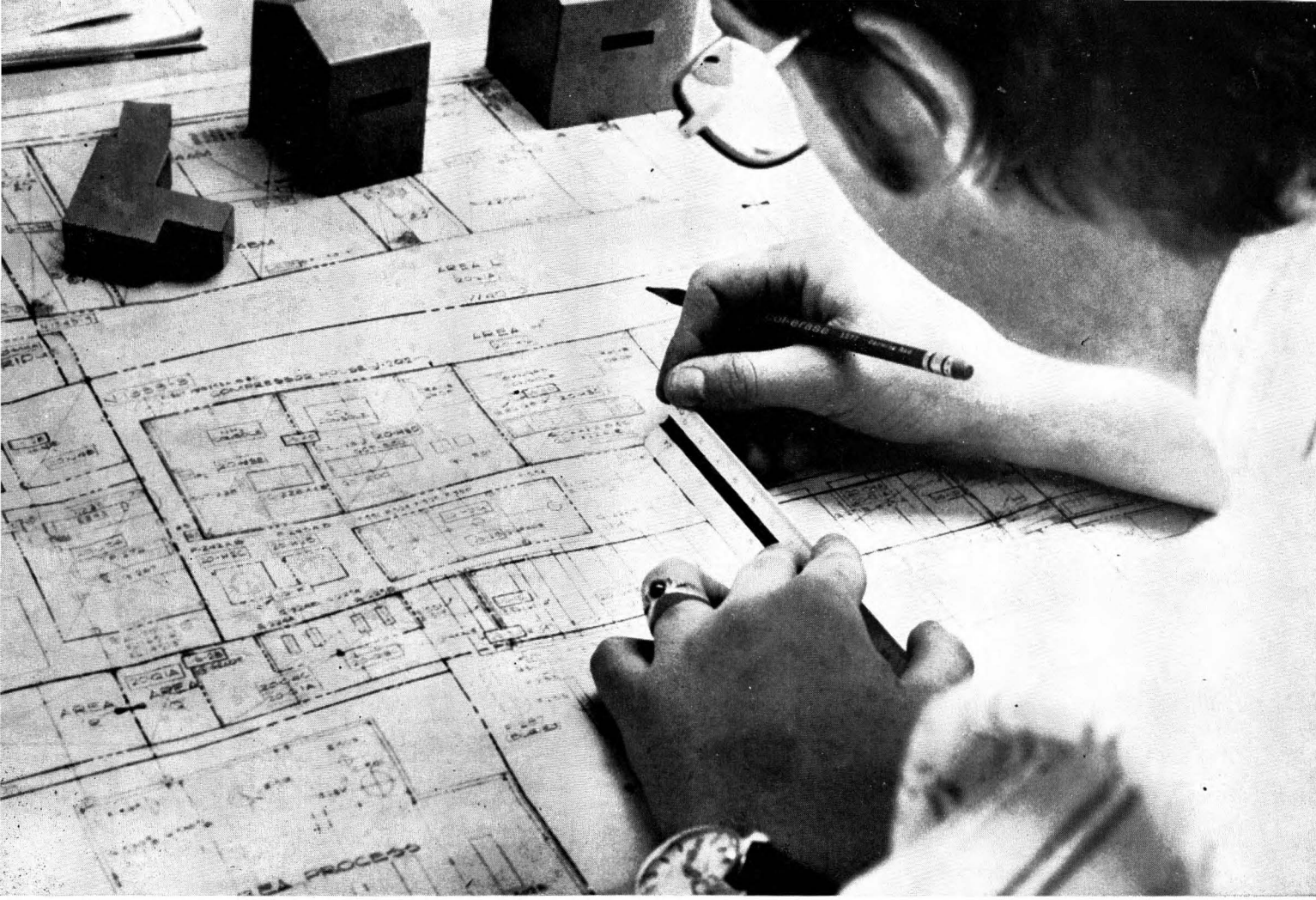

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THE ENGINEER AS AN ENTREPRENEUR - SOME NEW CONCEPTS

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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.

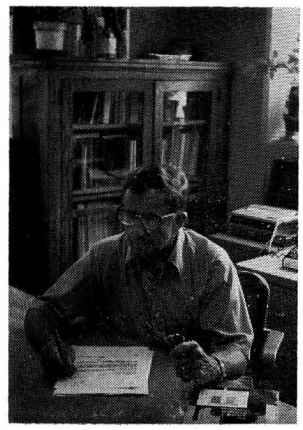
MARKETING RESEARCH

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.



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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.

A Course in

ENERGY, MASS AND MOMENTUM TRANSPORT -

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

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THE ABILTY 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 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.

. . . 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.

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 folowing 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. napthalene 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,

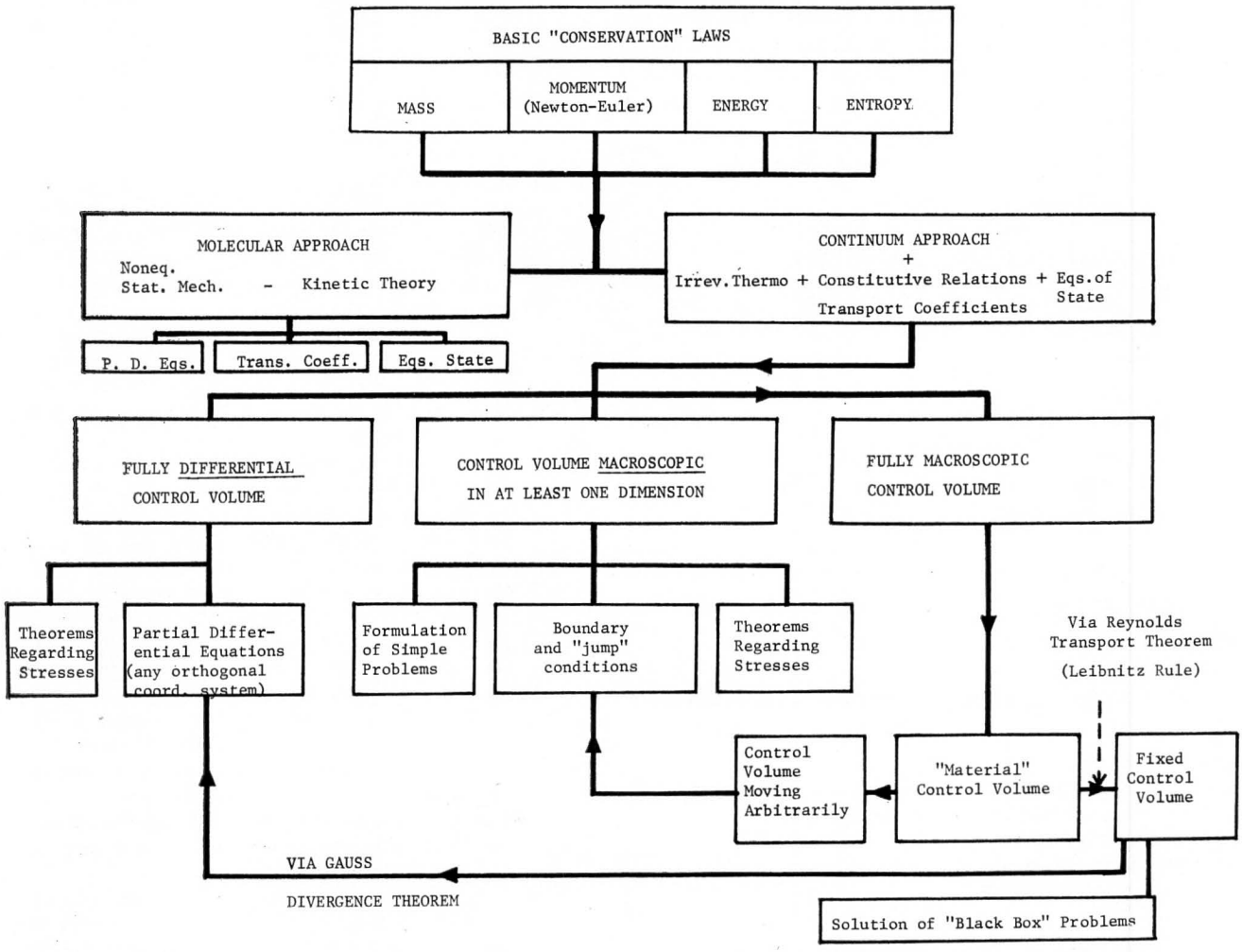
across an interface (eg. phase boundary) violate any basic conservation principle? b) Would a discontinuity in temperature, T, across an interface (eg. a shock wave) violate any conservation principle? c) Would a discontinuity in chemical potential across an interface (eg. a phase boundary) violate any 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

$$\underset{1}{\partial\rho_i''/t} + \underset{2}{\mathbf{div}'' \cdot (\rho_i'' \mathbf{v}_{s,t} + \mathbf{j}_i')} + \underset{3}{[\rho_i''' (\mathbf{v} - \mathbf{v}_s) + \mathbf{j}_i''] \cdot \mathbf{n}_+} = r_i'' \qquad (1)$$

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:

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

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 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:

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

or

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

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 nonzero 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

. . . 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.

*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.

*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 use 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 Entrepeneur

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. □

IMPLEMENTATION OF SI UNITS IN CHEMICAL ENGINEERING EDUCATION

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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. □

ChE book reviews

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 mitochrondria 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 invluded 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. □

1.25-THIS IS A LOG TABLE?

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YES, IF YOU can remember that:
$10^{0.1} = 1.25$, 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:
$10^{0.1} = 1.25$* and $10^{0.1}(10^{0.1}) = 10^{0.2}$
i.e., $1.25(1.25) = 1.56 \simeq 1.6$ we received
$10^{0.2} = 1.6$. In the same way,
$10^{0.1}(10^{0.2}) = 10^{0.3}$, $1.25(1.6) = 2.0$, we already calculated $10^{0.3} = 2.00$.
In summary:

$$10^{0.1} = 1.25$$
$$10^{0.2} = 1.6$$
$$10^{0.3} = 2.0$$

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 $10^{0.2}(10^{0.2}) = 10^{0.4}$, $1.6(1.6) = 2.5$, 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; sooned 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 $(10^{0.1})^{10} = 1.25(1.25)_2$ $(1.25)_3 \ldots (1.25)_{10} = ?$. 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-

*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.

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: $200 = 2 \times 100 \simeq 10^{0.3}(10^2) = 10^{2.3}$, $(10^{2.3})^{0.36} = 10^{2.3 \times 0.36} \cong 10^{0.83}$, and $0.36 = 3.6(10^{-1})$ and since $10^{0.5} = 3.2$ and $10^{0.6} = 4.0$, $0.36 \simeq 10^{0.55}(10^{-1})$ 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 $10^{0.3} = 2.0$, $10^{0.38} \cong 2.4$.
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 be checked for commercial feasibility [2]. For this reaction:

$$CH_3CHO \rightleftharpoons C_2H_4O$$

the equilibrium constant at 1000°K is:

ln K = −17.4. How much ethylene oxide can we expect?

$$K = e^{-17.4} = 10^{-17.4/2.3} = 10^{-7.6} = 10^{0.4}(10^{-8})$$
$$K = 2.5(10^{-8}) = 25(10^{-9}) = 25\ PPB$$

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)

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

$$10^{-\frac{E}{(2)\,(1000)\,(2.3)}\left(\frac{1000}{400} - \frac{1000}{300}\right)} = 8$$

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

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

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

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. □

Dr. Berty received his Diploma in Chemical Engineering from the Technical University of Budapest, Hungary in 1944 and his D.Sc. in 1950. He joined the Hungarian Oil and Gas Research Institute and taught in the College for Chemical Engineering in Veszprem, Hungary. In 1956 he accepted a Guest Professorship in Halle, East Germany. In 1957 he came to the U.S.A. and joined Union Carbide Corporation where he worked for 19 years. In the 1973/74 academic year he was a Senior Fulbright Lecturer at the Technical University in Munich, Germany. Presently he is with Autoclave Engineers, Inc.

REFERENCES

1. Calderbank and Pogorski, *Trans. Inst. Chem. Engrs.* (London), *35*, 195 (1957).
2. Kobe, K. A. and Associates, "Thermochemistry for the Petrochemical Industry." Reprinted from *The Petroleum Refiner*, January 1949 to December 1951.
3. Berty, J. M., *Chem. Eng. Prog.*, Vol. 70, No. 5, pp. 78-84, May, 1974.

CHEMICAL ENGINEERING EDUCATION INDEX Volumes VI-X

AUTHOR INDEX

TITLE INDEX

SUBJECT INDEX

UNIVERSITY OF ALBERTA

EDMONTON, ALBERTA, CANADA

Graduate Programs in Chemical Engineering

Financial Aid

Ph.D. Candidates: up to $6,500/year.
M.Sc. Candidates: up to $6,000/year.

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13 Professors, 20 Research Associates
30 Graduate Students.

Applications

For additional information write to:

Chairman
Department of Chemical Engineering
University of Alberta
Edmonton, Alberta, Canada T6G 2E6

Faculty and Research Interests

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

JAMES WM. WHITE, Assoc. Professor
Ph.D., University of Wisconsin, 1968
Real-Time Computing, Process Instrumentation and Control, Model Building and Simulation

Tucson has an excellent climate and many recreational opportunities. It is a growing, modern city of 400,000 that retains much of the old Southwestern atmosphere.

For further information, write to:

Dr. J. O. L. Wendt
Graduate Study Committee
Department of
Chemical Engineering
University of Arizona
Tucson, Arizona 85721

The University of Calgary

Program of Study

The Department of Chemical Engineering provides unusual opportunities for research and study leading to the M.Eng., M.Sc. or Ph.D. degrees. This dynamic department offers a wide variety of course work and research in the following areas: Petroleum Reservoir Engineering, Environmental Engineering, Fluid Mechanics, Heat Transfer, Mass Transfer, Process Engineering, Rheology and Thermodynamics. The University operates on an eight-month academic year, thus allowing four full months per year for research.

The requirements for the M.Eng. and M.Sc. degrees are 6 to 8 courses with a B standing or better and the submission of a thesis on a research project.

The requirements for the Ph.D. degree are 8 to 12 courses and the submission of a thesis on an original research topic.

The M.Eng. program is a part-time program designed for those who are working in industry and would like to enhance their technical education. The M.Eng. thesis is usually the design type and related to the industrial activity in which the student is engaged. Further details of this program are available from the Department Head, or the Chairman of the Graduate Studies Committee.

Research Facilities

The Department of Chemical Engineering occupies one wing of the Engineering Complex. The building was designed to accommodate the installation and operation of research equipment with a minimum of inconvenience to the researchers. The Department has at its disposal an EA1 690 hybrid computer and a TR48 analog computer and numerous direct access terminals to the University's CDC Cyber 172 digital computer. In addition, a well equipped Machine Shop and Chemical Analysis Laboratory are operated by the Department. Other major research facilities include a highly instrumented and versatile multiphase pipeline flow loop, an automated pilot plant unit based on the Girbotol Process for natural gas processing, an X-ray scanning unit for studying flow in porous media, a fully instrumented adiabatic combustion tube for research on the in-situ recovery of hydrocarbons from oil sands, a laser anemometer unit, and environmental research laboratories for air pollution, water pollution and oil spill studies.

Financial Aid

Fellowships and assistantships are available with remuneration of up to $6,000 per annum, with possible remission of fees. In addition, new students may be eligible for a travel allowance of up to a maximum of $300. If required, loans are available from the Federal and Provincial Governments to Canadian citizens and Landed Immigrants. There are also a number of bursaries, fellowships, and scholarships available on a competition basis to full-time graduate students. Faculty members may also provide financial support from their research grants to students electing to do research with them.

Cost of Study

The tuition fees for a full-time graduate student are $625 per year plus small incidental fees. Most full-time graduate students to date have had their tuition fees remitted.

Cost of Living

Housing for single students in University dormitories range from $172/mo. for a double room, to $205/mo. for a single room, including board. There are a number of new townhouses for married students available, ranging from $177/mo. for a 1-bedroom, to $193/mo. for a 2-bedroom and to $209/mo. for a 3-bedroom unit, including utilities, major appliances and parking. Numerous apartments and private housing are within easy access of the University. Food and clothing costs are comparable with those found in other major North American urban centres.

Student Body

The University is a cosmopolitan community attracting students from all parts of the globe. The current enrolment is about 12,000 with approximately 1,000 graduate students. Most full-time graduate students are currently receiving financial assistance either from internal or external sources.

The Community

The University is located in Calgary, Alberta, home of the world famous Calgary Stampede. This city of 570,000 combines the traditions of the Old West with the sophistication of a modern, dynamic urban centre. Beautiful Banff National Park is 60 miles from the city and the ski resorts of the Banff and Lake Louise areas are readily accessible. Jasper National Park is only five hours away by car via one of the most scenic highways in the Canadian Rockies. A wide variety of cultural and recreational facilities are available both on campus and in the community at large. Calgary is the business centre of the petroleum industry in Canada and as such has one of the highest concentrations of engineering activity in the country.

The University

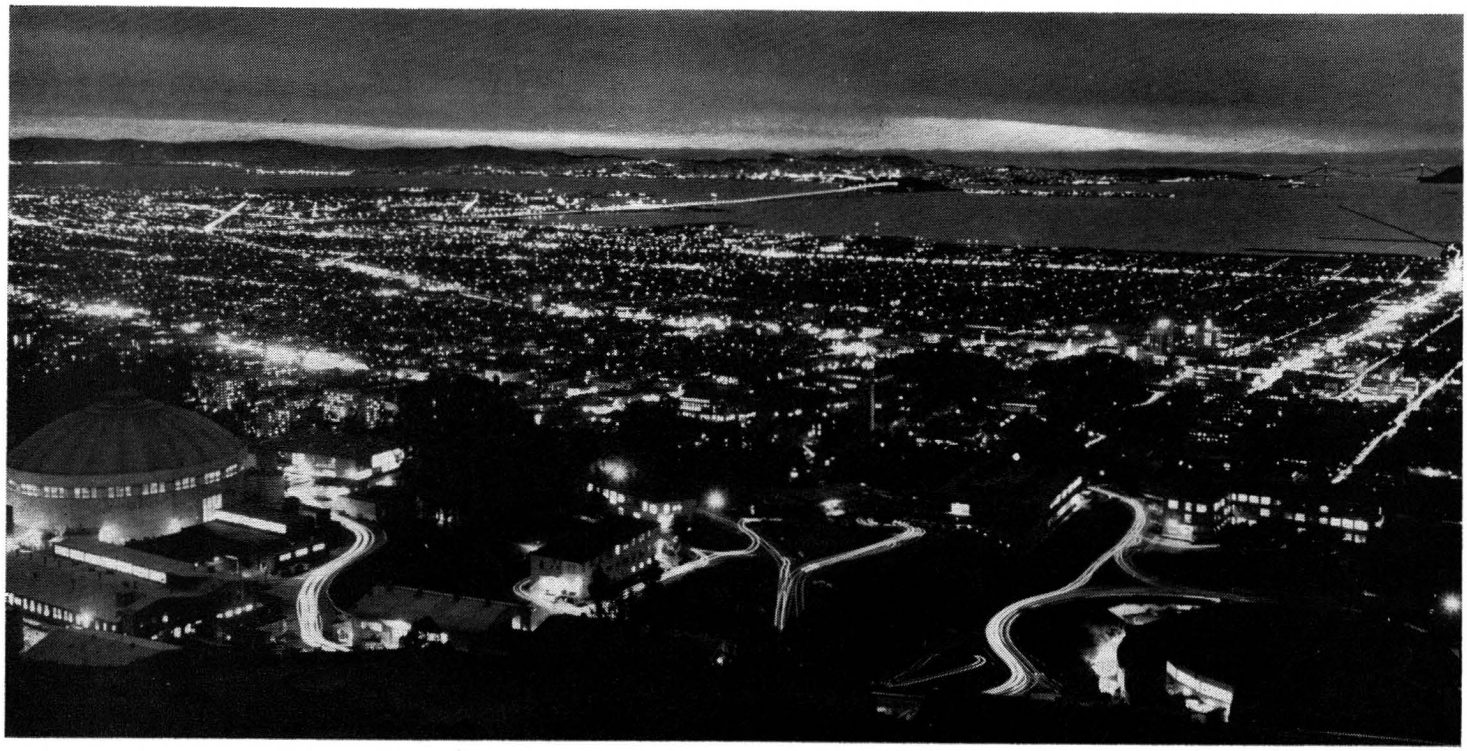
The University operated from 1945 until 1966 as an integral part of the University of Alberta. The present campus situated in the rolling hills of northwest Calgary, was established in 1960, and in 1966 The University of Calgary was chartered as an autonomous institution by the Province of Alberta. At present the University consists of 14 faculties. Off-campus institutions associated with The University of Calgary include the Banff School of Fine Arts and Centre of Continuing Education located in Banff, Alberta, and the Kananaskis Environmental Research Station located in the beautiful Bow Forest Reserve.

Applying

The Chairman, Graduate Studies Committee
Department of Chemical Engineering
The University of Calgary
Calgary, Alberta T2N 1N4
Canada

UNIVERSITY OF CALIFORNIA

BERKELEY, CALIFORNIA



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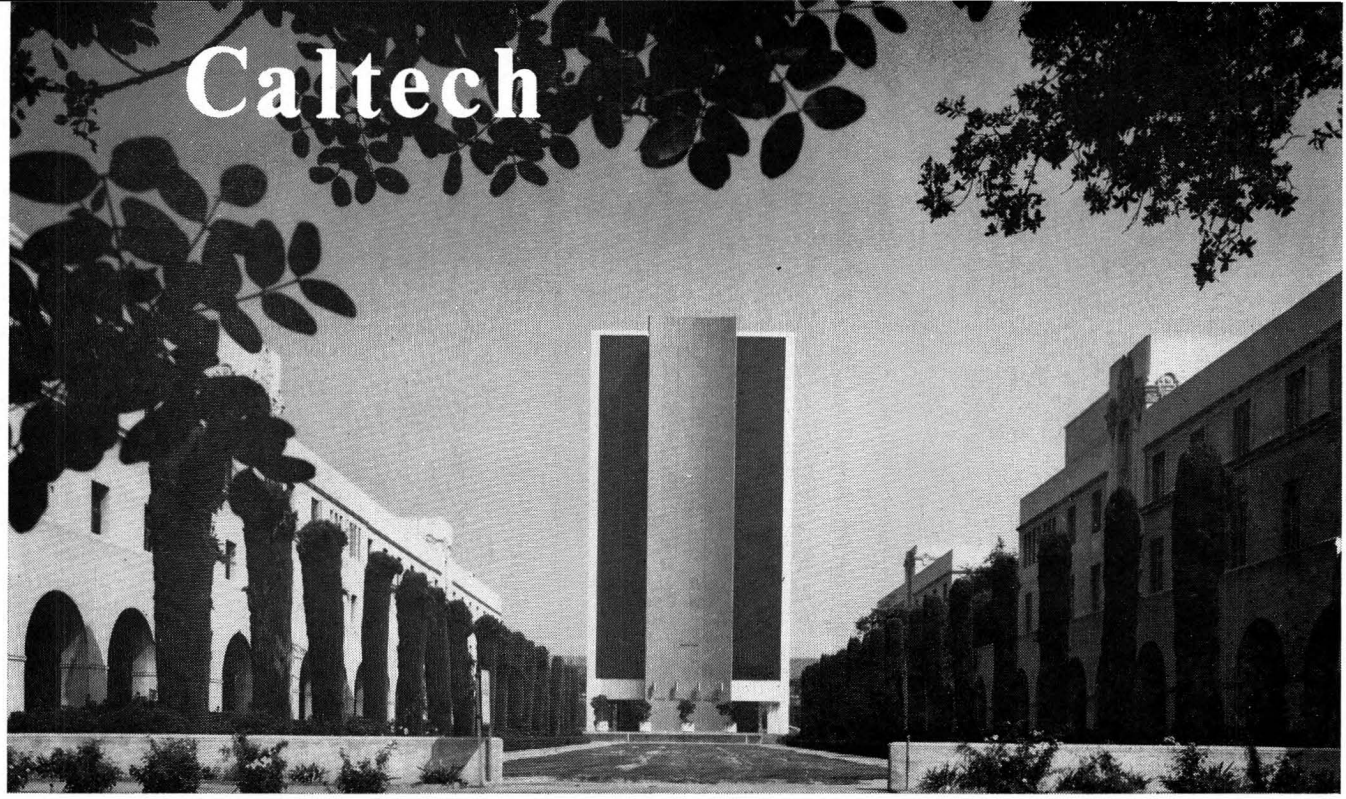
Theodore Vermuelen
Charles R. Wilke
Michael C. Williams

FOR APPLICATIONS AND FURTHER INFORMATION, WRITE:

Department of Chemical Engineering
UNIVERSITY OF CALIFORNIA
Berkeley, California 94720



PROGRAM OF STUDY Distinctive features of study in chemical engineering at the California Institute of Technology are the creative research atmosphere in which the student finds himself and the strong emphasis on basic chemical, physical, and mathematical disciplines in his program of study. In this way a student can properly prepare himself for a productive career of research, development, or teaching in a rapidly changing and expanding technological society.

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APPLICATIONS Further information and an application form may be obtained by writing

Professor J. H. Seinfeld
Executive Officer for Chemical Engineering
California Institute of Technology
Pasadena, California 91125

It is advisable to submit applications before February 15, 1977.

FACULTY IN CHEMICAL ENGINEERING

WILLIAM H. CORCORAN, Professor and Vice-President for Institute Relations
Ph.D. (1948), California Institute of Technology
Kinetics and catalysis; biomedical engineering; air and water quality.

SHELDON K. FRIEDLANDER, Professor
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
Theoretical and experimental fluid mechanics; heat and mass transfer; suspension rheology; mechanics of non-Newtonian fluids.

CORNELIUS J. PINGS, Professor,
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,
Executive Officer
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.

ROBERT W. VAUGHAN, Associate Professor
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Solid state and surface chemistry.

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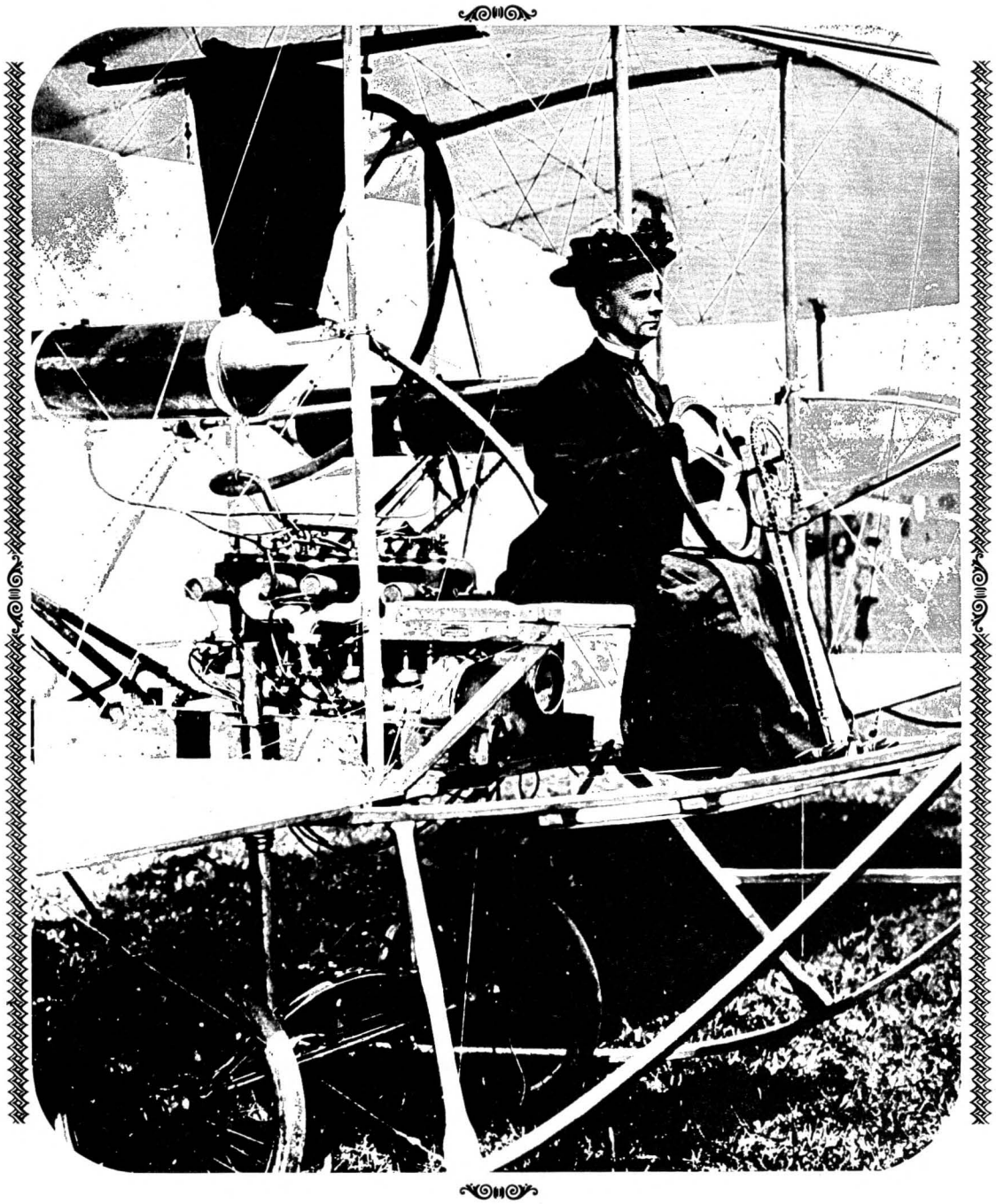

Graduate Chemical Engineering

Carnegie-Mellon University
Schenley Park Pittsburgh Pennsylvania 15213

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in

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at

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of

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Laser Doppler Velocimetry
Chemical Reaction Engineering

FINANCIAL AID

Fellowships, Teaching Assistantships and Research Assistantships are available to qualified applicants. Applications are welcome from graduates in Chemistry and Chemical Engineering.

FOR FURTHER INFORMATION

Contact: Graduate Student Advisor
Chemical Engineering Department
Case Western Reserve University
Cleveland, Ohio 44106

DEPARTMENT OF CHEMICAL ENGINEERING

CLARKSON

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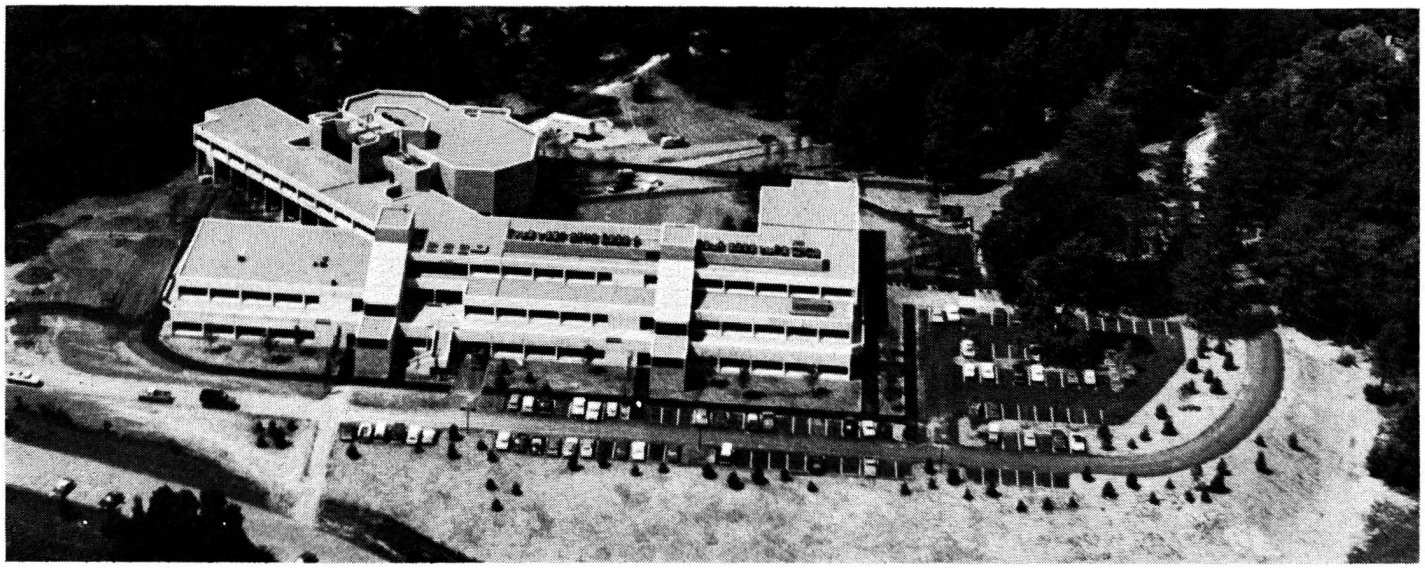

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W.R. WILCOX—Prof. and Chmn. (Ph.D., 1960, University of California, Berkeley) Crystal growth phenomena, new separation techniques.

M. G. ANTONIADES—Asst. Prof. (Ph.D., 1976, University of Rochester) Surface films at fluid interfaces, interfacial reactions, interphase mass transfer.

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.

H. L. SHULMAN—Prof., Dean of Eng. and Vice Pres of the College. (Ph.D., 1950, University of Pennsylvania) Mass Transfer, packed columns, adsorption of gases, absorption.

R. S. SUBRAMANIAN—Asst. Prof. (Ph.D., 1972, Clarkson College of Technology) Heat and mass transfer, unsteady convective diffusion — miscible dispersion, chromatographic and other interphase transport systems, fluid mechanics, mathematical modeling.

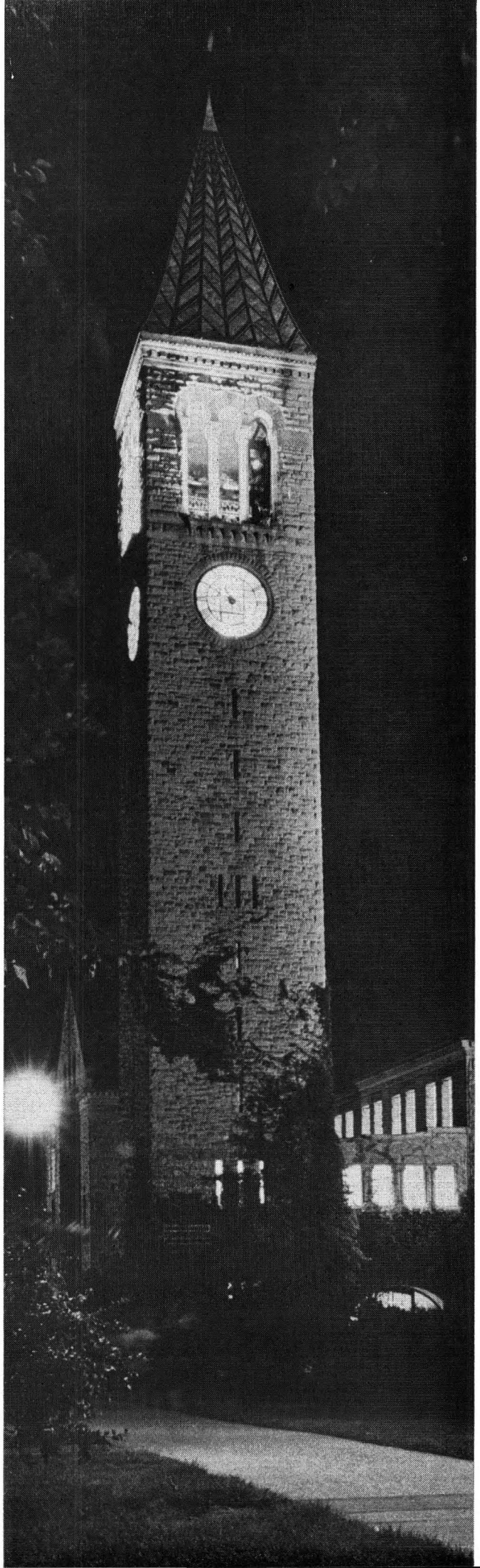
P. C. SUKANEK—Asst. Prof. (Ph.D., 1972, University of Massachusetts) Rheology, polymer degradation, continuum mechanics.

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.

For information concerning Assistantships and Fellowships contact the Dean of the Graduate School, Clarkson College of Technology, Potsdam, New York 13676

CLARKSON COLLEGE OF TECHNOLOGY / POTSDAM, NEW YORK 13676



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Three graduate degree programs in several subject areas are offered in the Field of Chemical Engineering at Cornell University. Students may enter a research-oriented course of study leading to the degrees of Doctor of Philosophy or Master of Science, or may study for the professional degree of Master of Engineering (Chemical). Graduate work may be done in the following subject areas.

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Bioengineering

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Chemical Microscopy

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Kinetics and Transport Processes.

Homogeneous kinetics; catalysis by solids and enzymes; catalyst deactivation; simultaneous mass transfer and reaction; diffusion in liquids and membranes.

Chemical Processes and Process Control

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Materials Engineering

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Nuclear Process Engineering

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Faculty Members and Research Interests

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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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Newark, Delaware 19711

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D. V. Boger

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W. H. Manogue ——— Catalysis, reaction engineering
F. E. Rush, Jr. ——— Mass transfer—distillation, absorption, extraction
R. J. Samuels ——— Polymer science
A. B. Stiles ——— Catalysis
K. F. Wissbrun ——— Polymer engineering
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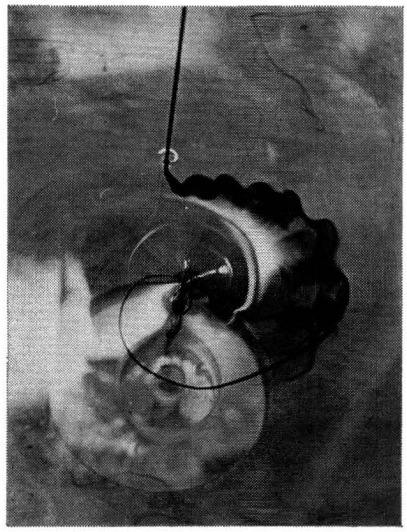

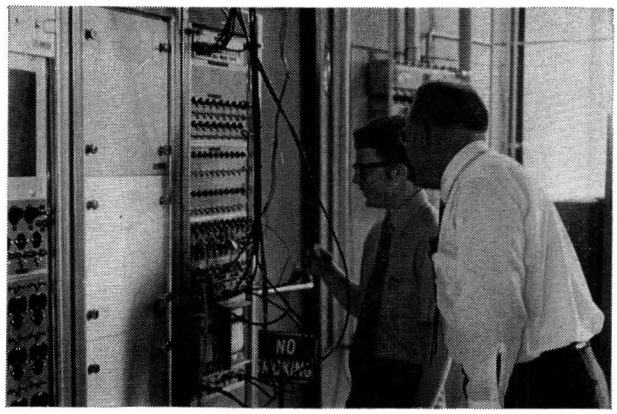

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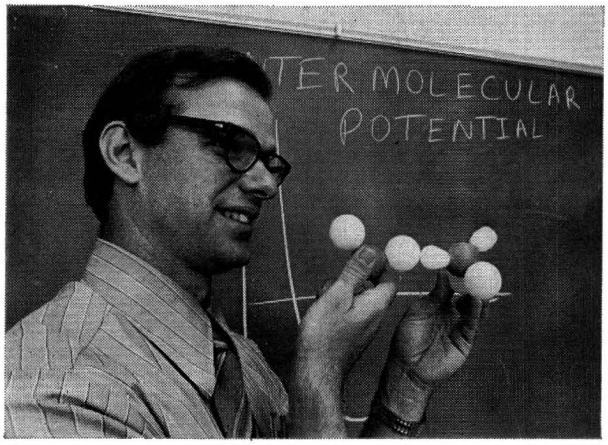

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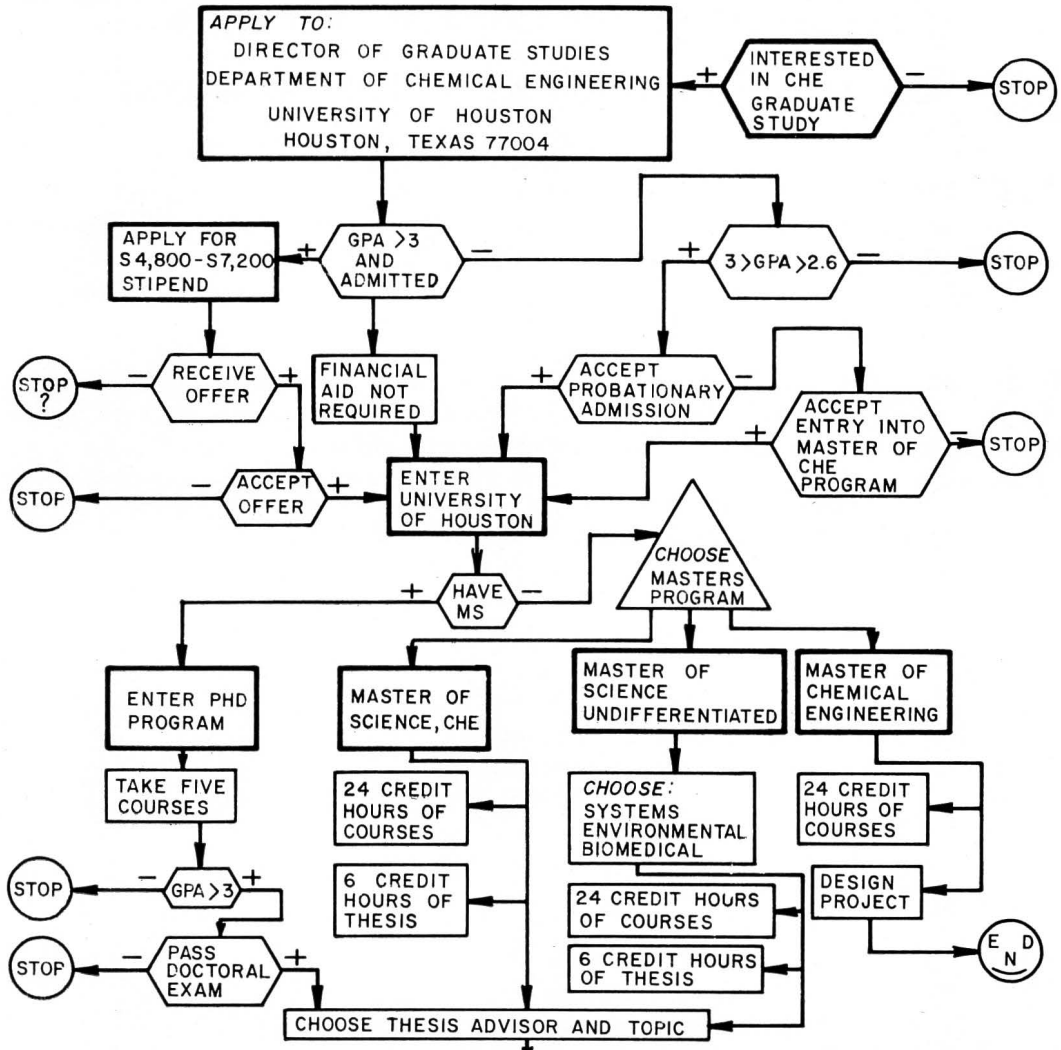

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UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

- **GOALS OF GRADUATE STUDY:** This Department offers M.S. and Ph.D. programs with a strong emphasis on creative research, either in fundamental engineering science or its application to the solution of current problems of social concern. Truly exceptional educational experiences may be achieved from the close one-to-one interaction of a student with a professor as together they develop relevant scientific contributions.

- **STAFF AND FACILITIES:** The faculty of the Department are all highly active in both teaching and research; they have won numerous national and international awards for their achievements. Moreover, outstanding support for graduate research is available, not only in terms of equipment and physical facilities but also from the many shops, technicians, and service personnel.

- **AREAS OF RESEARCH:** Applied Mathematics
  Biological Applications of Chemical Engineering
  Chemical Kinetics
  Chemical Reactor Dynamics
  Corrosion
  Electronic Structure of Matter
  Electrochemical Engineering
  Energy Sources and Conservation
  Environmental Engineering
  Fluid Dynamics
  Heat Transfer
  High Pressure
  Mass Transfer
  Materials Science and Engineering
  Molecular Thermodynamics
  Phase Transformations
  Process Control
  Process Design
  Reaction Engineering
  Statistical Mechanics
  Systems Analysis
  Two-Phase Flow

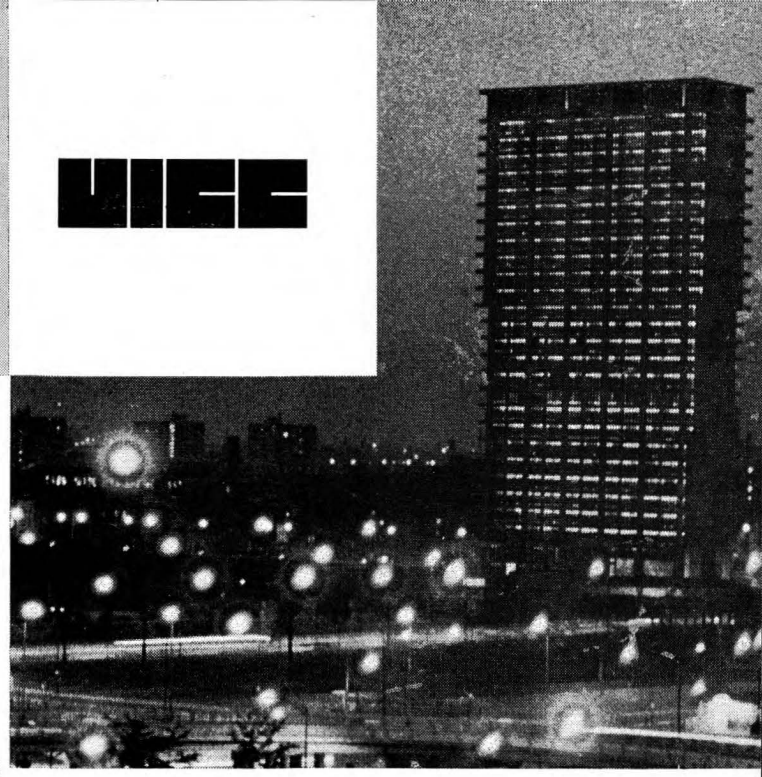
- **FOR INFORMATION AND APPLICATIONS:** **Professor J. W. Westwater**
  Department of Chemical Engineering
  113 Adams Laboratory
  University of Illinois
  Urbana, Illinois 61801

GRADUATE STUDY AND RESEARCH

The Department of Energy Engineering

UNIVERSITY OF ILLINOIS AT CHICAGO CIRCLE

UICC



Graduate Programs in

The Department of Energy Engineering

leading to the degrees of

MASTER OF SCIENCE and

DOCTOR OF PHILOSOPHY

Faculty and Research Activities in CHEMICAL ENGINEERING

Paul M. Chung
Ph.D., University of Minnesota, 1957
Professor and Head of the Department

Fluid mechanics, combustion, turbulence, chemically reacting flows

David S. Hacker
Ph.D., Northwestern University, 1954
Associate Professor

Chemical kinetics, mass transport phenomena, chemical process design, particulate transport phenomena

John H. Kiefer
Ph.D., Cornell University, 1961
Professor

Kinetics of gas reactions, energy transfer processes, molecular lasers

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

Multi-phase flow, flow in porous media, mass transfer, interfacial behavior, biological applications of transport phenomena, thermodynamics of solutions

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

Thermodynamics and statistical mechanics of fluids, solids, and solutions, kinetics of liquid reactions, cryobioengineering

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

Thermodynamics, biotransport, artificial organs, biophysics

Satish C. Saxena
Ph.D., Calcutta University, 1956
Professor

Transport properties of fluids and solids, heat and mass transfer, isotope separation, fixed and fluidized bed combustion

Stephen Szépe
Ph.D., Illinois Institute of Technology, 1966
Associate Professor

Catalysis, chemical reaction engineering, optimization, environmental and pollution problems

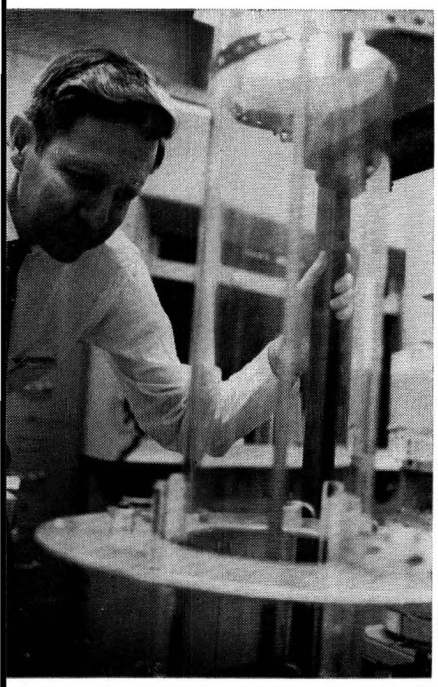
The MS program, with its optional thesis, can be completed in one year.

The department invites applications for admission and support from all qualified candidates. Special fellowships are available for minority students. To obtain application forms or to request further information write:

Professor W. J. Minkowyz, Chairman
The Graduate Committee
Department of Energy Engineering
University of Illinois at Chicago Circle
Box 4348, Chicago, Illinois 60680

IOWA STATE UNIVERSITY

OF SCIENCE AND TECHNOLOGY



Energy Conversion
(Coal Tech, Hydrogen Production, Atomic Energy)

Renato G. Bautista
Lawrence E. Burkhart
George G. Burnet
Allen H. Pulsifer
Dean L. Ulrichson
Thomas D. Wheelock

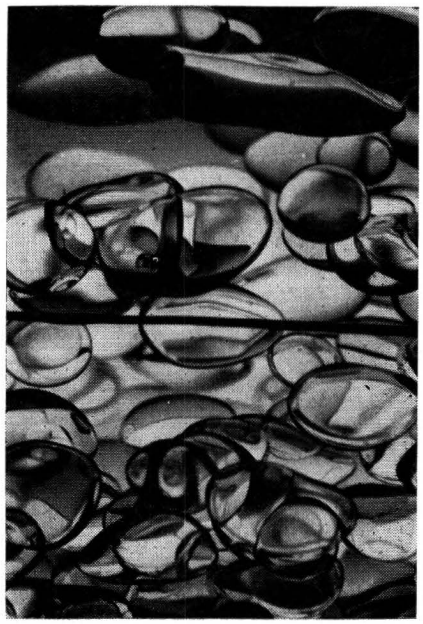
GRADUATE STUDY and GRADUATE RESEARCH in Chemical Engineering

Transport Processes
(Heat, mass & momentum transfer)

William H. Abraham
Renato G. Bautista
Charles E. Glatz
James C. Hill
Frank O. Shuck
Richard C. Seagrave

Process Chemistry and Fertilizer Technology

David R. Boylan
George Burnet
Maurice A. Larson



Biomedical Engineering

(System Modeling, Transport. process)
Richard C. Seagrave
Charles E. Glatz

Biochemical Engineering

(Enzyme Technology)
Charles E. Glatz
Peter J. Reilly

Polymerization Processes

Wiilliam H. Abraham
John D. Stevens

Crystallization Kinetics
Maurice A. Larson
John D. Stevens

Process Instrumentation and System Optimization and Control
Lawrence E. Burkhart
Kenneth R. Jolls

as well as

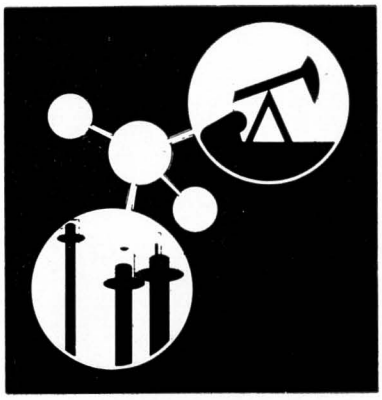
Air Pollution Control
Solvent Extraction
High Pressure Technology
Mineral Processing

write to:

Prof. D. L. Ulrichson
Dept. of Chem. Engr. & Nuc. Engr.
Iowa State University
Ames, Iowa 50010

UNIVERSITY OF KANSAS

Department of Chemical and Petroleum Engineering



M.S. and Ph.D. Programs
in
Chemical Engineering
M.S. Program
in
Petroleum Engineering
also
Doctor of Engineering (D.E.)
and
M.S. in Petroleum Management

The Department is the recent recipient of a large state grant for research in the area of Tertiary Oil Recovery to assist the Petroleum Industry.

Financial assistance is available for Research Assistants and Teaching Assistants

Research Areas

Transport Phenomena

Fluid Flow in Porous Media

Process Dynamics and Control
Water Resources and Environmental Studies

Mathematical Modeling of Complex Physical Systems

Reaction Kinetics and Process Design

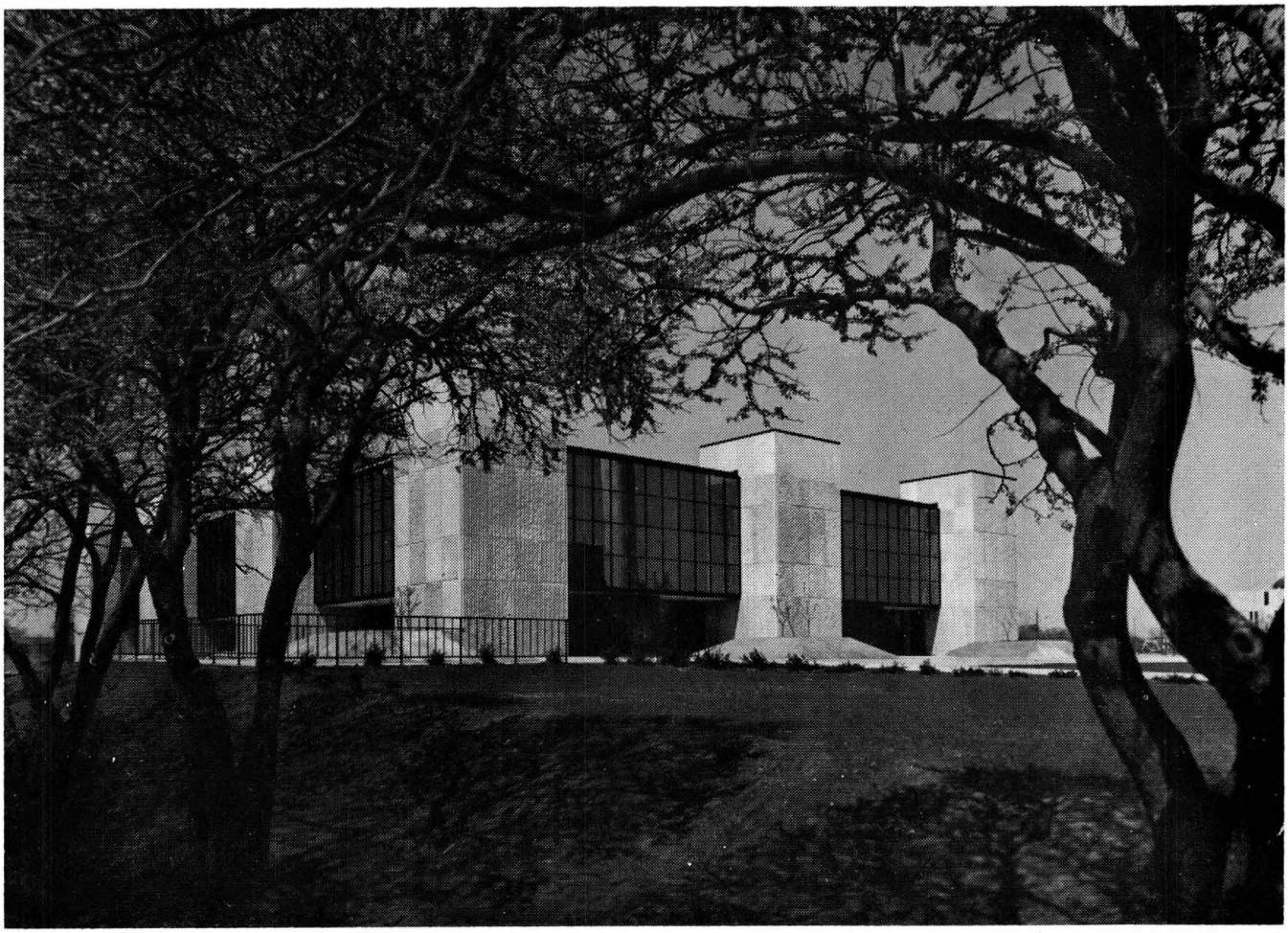
Nucleate Boiling

High Pressure, Low Temperature Phase Behavior

For Information and Applications write:

Floyd W. Preston, Chairman
Dept. of Chemical and Petroleum Engineering
University of Kansas
Lawrence, Kansas, 66044
Phone (913) UN4-3922

Graduate Study in Chemical Engineering
KANSAS STATE UNIVERSITY



DURLAND HALL—New Home of Chemical Engineering

M.S. and Ph.D. programs in Chemical Engineering and Interdisciplinary Areas of Systems Engineering, Food Science, and Environmental Engineering.

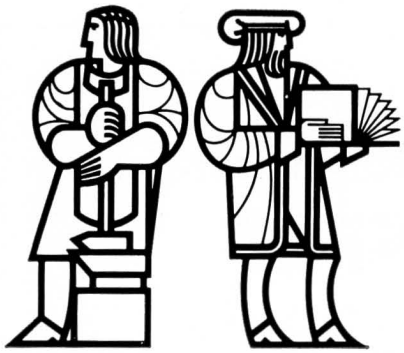
Financial Aid Available
Up to $5,000 Per Year

FOR MORE INFORMATION WRITE TO

Professor B. G. Kyle
Durland Hall
Kansas State University
Manhattan, Kansas 66502

AREAS OF STUDY AND RESEARCH

DIFFUSION AND MASS TRANSFER
HEAT TRANSFER
FLUID MECHANICS
THERMODYNAMICS
BIOCHEMICAL ENGINEERING
PROCESS DYNAMICS AND CONTROL
CHEMICAL REACTION ENGINEERING
MATERIALS SCIENCE
SOLID MIXING
CATALYSIS
OPTIMIZATION
FLUIDIZATION
PHASE EQUILIBRIUM



Massachusetts Institute of Technology

DEPARTMENT OF CHEMICAL ENGINEERING

- ENVIRONMENTAL QUALITY
- BIOCHEMICAL ENGINEERING
- BIOMEDICAL ENGINEERING
- TRANSPORT PHENOMENA
- CHEMICAL ENGINEERING SYSTEMS
- SURFACE CHEMISTRY AND TECHNOLOGY
- POLYMERS AND MACROMOLECULES
- ENERGY

For decades to come, the chemical engineer will play a central role in fields of national concern. In two areas alone, energy and the environment, society and industry will turn to the chemical engineer for technology and management in finding process-related solutions to critical problems. MIT has consistently been a leader in chemical engineering education with a strong working relationship with industry for over a half century. For detailed information, contact Professor Kenneth A. Smith, Acting Head of the Department of Chemical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139.

FACULTY

Raymond F. Baddour
Janos M. Beer
Clark K. Colton
Lawrence B. Evans
Hoyt C. Hottel
Jack B. Howard
John P. Longwell
Herman P. Meissner
Edward W. Merrill
J. Th. G. Overbeek
Robert C. Reid
Adel F. Sarofim
Charles N. Satterfield
Kenneth A. Smith
J. Edward Vivian
Glenn C. Williams
Michael Modell
Ronald A. Hites
Robert C. Armstrong
Lloyd A. Clomburg
Robert E. Cohen
William M. Deen
Richard G. Donnelly
Christos Georgakis
Michael P. Manning
Frederick A. Putnam
Jefferson W. Tester

Department of Chemical Engineering

UNIVERSITY OF MISSOURI — ROLLA

ROLLA, MISSOURI 65401

Contact Dr. M. R. Strunk, Chairman

Day Programs M.S. and Ph.D. Degrees

Established fields of specialization in which research programs are in progress are:

(1) Fluid Turbulence Mixing and Drag Reduction Studies—Drs. J. L. Zakin and G. K. Patterson

(2) Electrochemistry and Fuel Cells—Dr. J. W. Johnson

(3) Heat Transfer (Cryogenics) Dr. E. L. Park, Jr.

(4) Mass Transfer Studies—Dr. R. M. Wellek

In addition, research projects are being carried out in the following areas:

(a) Optimization of Chemical Systems; Energy Conversion from Agricultural Products—Prof. J. L. Gaddy

(b) Design Techniques and Fermentation Studies —Dr. M. E. Findley

(c) Multi-component Distillation Efficiencies and Separation Processes—Dr. R. C. Waggoner

(d) Separations by Electrodialysis Techniques—Dr. H. H. Grice

(e) Process Dynamics and Control; Computer Applications to Process Control—Ds. M. E. Findley, R. C. Waggoner, and R. A. Mollenkamp

(f) Transport Properties, Kinetics, enzymes and catalysis—Dr. O. K. Crosser and Dr. B. E. Poling

(g) Thermodynamics, Vapor-Liquid Equilibrium —Dr. D. B. Manley

Financial aid is obtainable in the form of Graduate and Research Assistantships, and Industrial Fellowships. Aid is also obtainable through the Materials Research Center.

university of

pennsylvania chemical and biochemical engineering

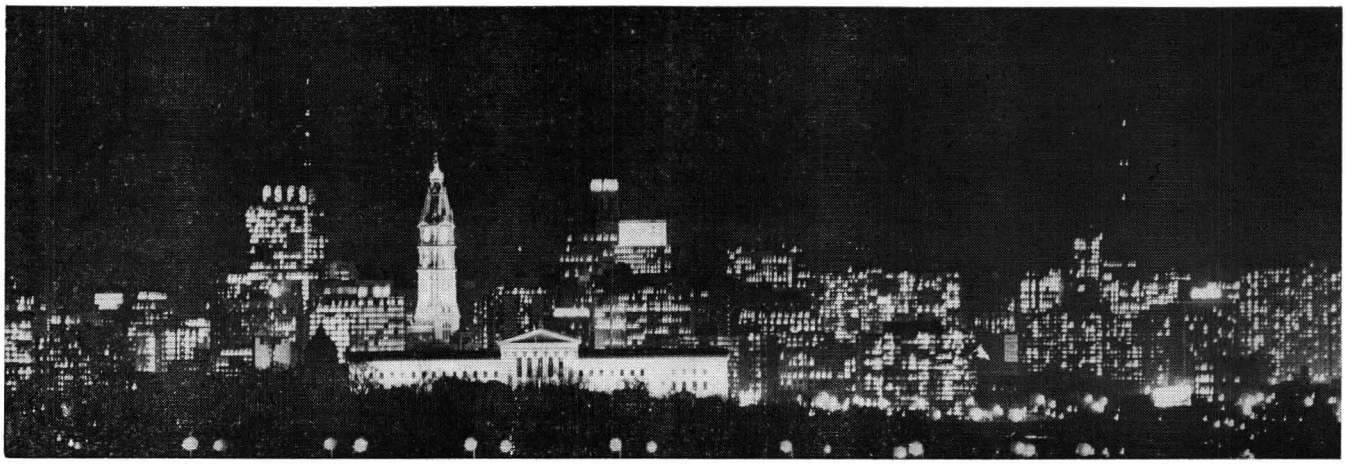
FACULTY

Stuart W. Churchill (Michigan)
Elizabeth B. Dussan V. (Johns Hopkins)
William C. Forsman (Pennsylvania)
Eduardo D. Glandt (Pennsylvania)
David J. Graves (M.I.T.)
A. Norman Hixson (Columbia)
Arthur E. Humphrey (Columbia)
Mitchell Litt (Columbia)
Alan L. Myers (California)
Melvin C. Molstad (Yale)
Daniel D. Perlmutter (Yale)
John A. Quinn (Princeton)
Warren D. Seider (Michigan)

RESEARCH SPECIALTIES

Energy Utilization
Enzyme Engineering
Biochemical Engineering
Biomedical Engineering
Computer-Aided Design
Chemical Reactor Analysis
Environmental and Pollution Control
Polymer Engineering
Process Simulation
Surface Phenomena
Separations Techniques
Transport Phenomena

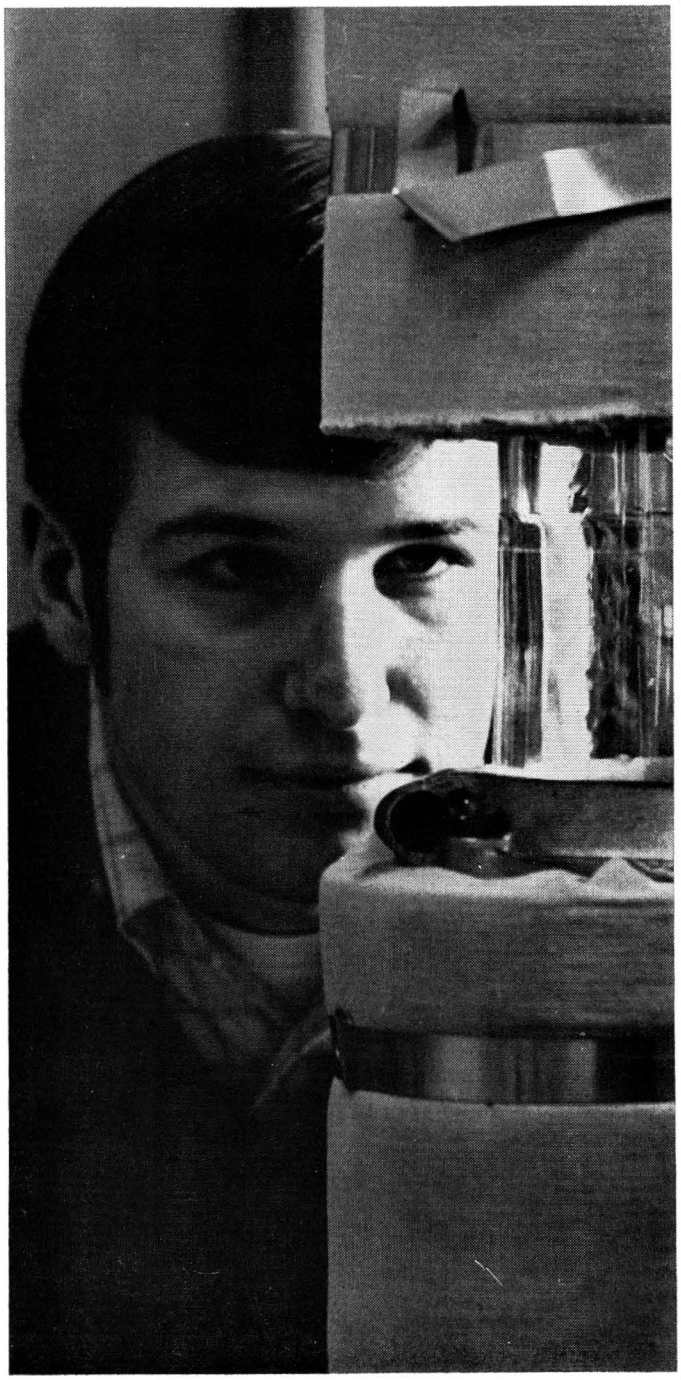
The faculty includes two members of the National Academy of Engineering and three recipients of the highest honors awarded by the American Institute of Chemical Engineers. Staff members are active in teaching, research, and professional work. Located near one of the largest concentrations of chemical industry in the United States, the University of Pensylvania maintains the scholarly standards of the Ivy League and numbers among its assets a superlative Medical Center and the Wharton School of Business.



PHILADELPHIA: The cultural advantages, historical assets, and recreational facilities of a great city are within walking distance of the University. Enthusiasts will find a variety of college and professional sports at hand. The Pocono Mountains and the New Jersey shore are within a two-hour drive.

For further information on graduate studies in this dynamic setting, write to Dr. A. L. Myers,
Department of Chemical and Biochemical Engineering / D3, University of Pennsylvania, Philadelphia, PA 19174.

LOOKING



for a

graduate education

in

Chemical Engineering ?

Consider

PENN STATE

M.S. and Ph.D. Programs Offered with Research In

Biomedical Engineering

Environmental Research

Reactor Design and Catalysis

Transport Phenomena

Thermodynamic Properties

Process Dynamics and Control

Applied Chemistry and Kinetics

Petroleum Refining

Tribology

Interfacial Phenomena

Energy Research

And Other Areas

WRITE TO

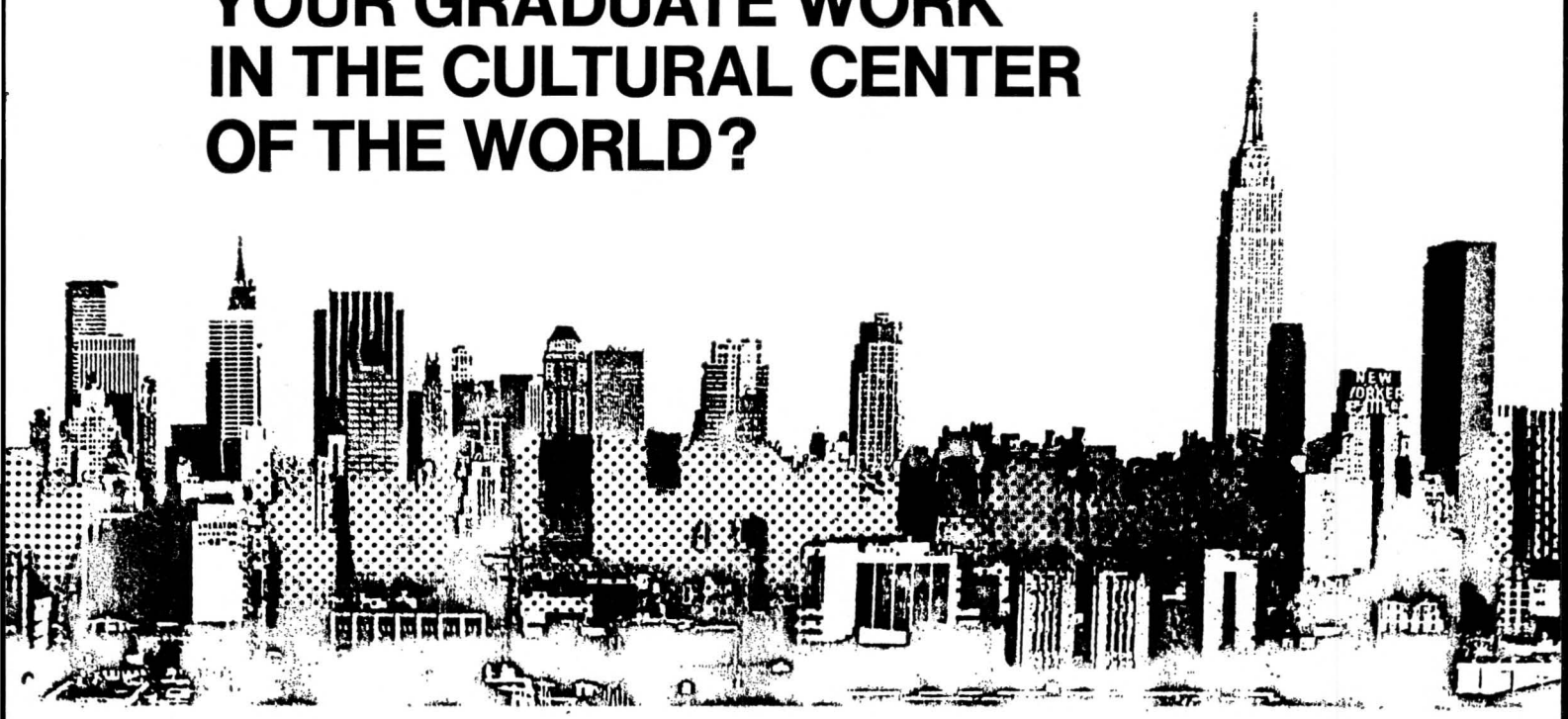
Prof. Lee C. Eagleton, Head

160 Fenske Laboratory

The Pennsylvania State University

University Park, Pa. 16802

HOW WOULD YOU LIKE TO DO YOUR GRADUATE WORK IN THE CULTURAL CENTER OF THE WORLD?



CHEMICAL ENGINEERING

POLYMER SCIENCE & ENGINEERING

FACULTY

R. C. Ackerberg
R. F. Benenati
J. J. Conti
C. D. Han
R. D. Patel
E. M. Pearce
E. N. Ziegler

RESEARCH AREAS

Air Pollution
Biomedical Systems
Catalysis, Kinetics and Reactors
Fluidization
Fluid Mechanics
Heat and Mass Transfer
Mathematical Modelling
Polymerization Reactions
Process Control
Rheology and Polymer Processing

Polytechnic Institute of New York

Formed by the merger of Polytechnic Institute of Brooklyn and New York University School of Engineering and Science.

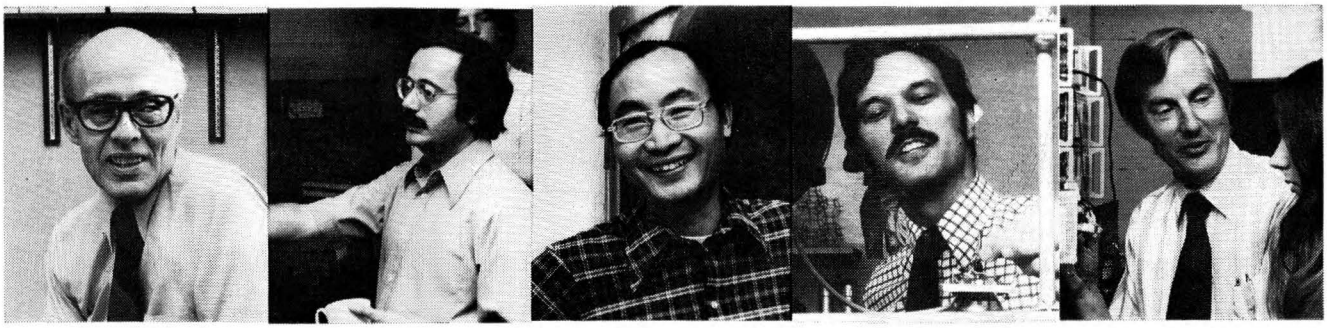
Fellowships and Research Assistantships are available.

Department of Chemical Engineering

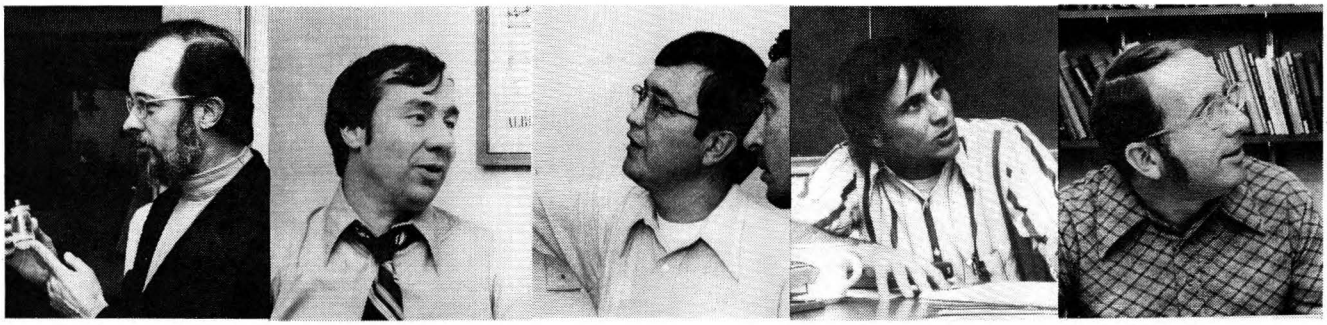
Programs leading to Master's, Engineer and Doctor's degrees. Areas of study and research: chemical engineering, polymer science and engineering and environmental studies.

For further information contact

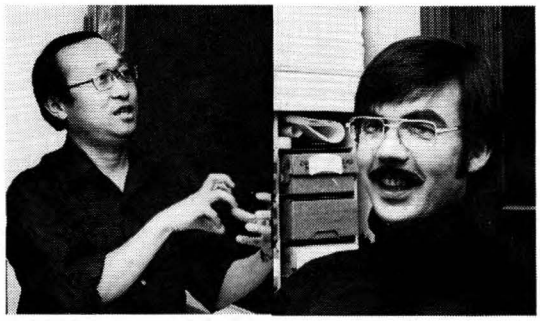
Professor C. D. Han
Head, Department of Chemical Engineering
Polytechnic Institute of New York
333 Jay Street
Brooklyn, New York 11201

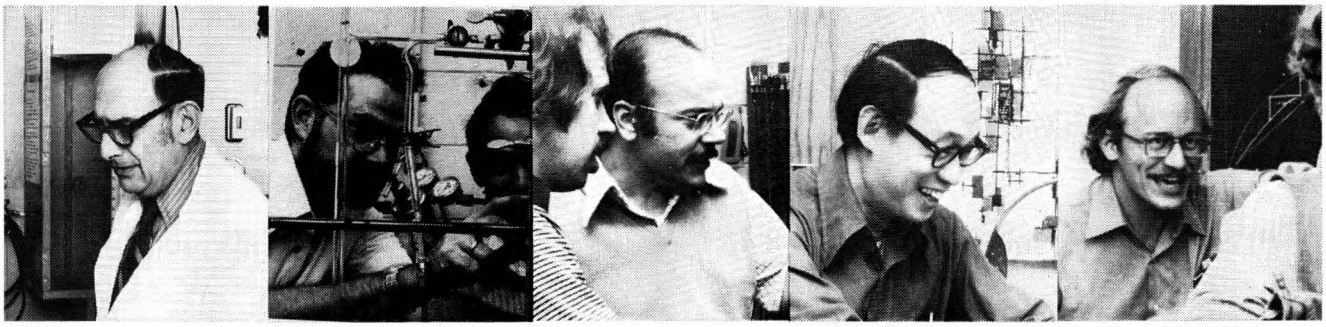


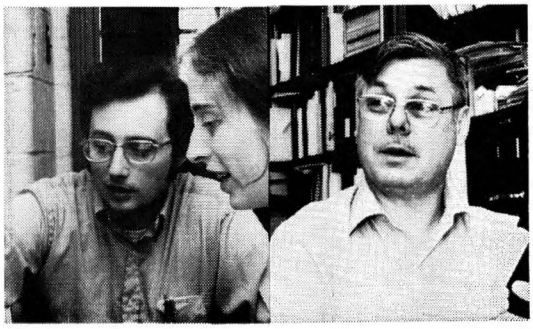
PURDUE



Albright
Barile
Chao
Delgass
Eckert
Emery
Greenkorn
Hanneman
Houze
Kessler
Koppel
Lim
Reklaitis
Sesonske
Squires
Theofanous
Tsao
Wankat
Weigand
Woods







Chemical Engineering
Purdue University
West Lafayette, Indiana 47907

Graduate Study in Chemical Engineering at Rice University

Graduate study in Chemical Engineering at Rice University is offered to qualified students with backgrounds in the fundamental principles of Chemistry, Mathematics, and Physics. The curriculum is aimed at strengthening the student's understanding of these principles and provides a basis for developing in certain areas the necessary proficiency for conducting independent research. A large number of research programs are pursued in various areas of Chemical Engineering and related fields, such as Biomedical Engineering and Polymer Science. A joint program with the Baylor College of Medicine, leading to M.D.-Ph.D. and M.D.-M.S. degrees is also available.

The Department has approximately 30 graduate students, predominantly Ph.D. candidates. There are also several post-doctoral fellows and research engineers associated with the various laboratories. Permanent faculty numbers 12, all active in undergraduate and graduate teaching, as well as in research. The high faculty-to-student ratio, outstanding laboratory facilities, and stimulating research projects provide a graduate education environment in keeping with Rice's reputation for academic excellence. The Department is one of the top 15 Chemical Engineering Departments in the U.S., ranked by graduate faculty quality and program effectiveness, according to a recent evaluation by the American Council of Education.

MAJOR RESEARCH AREAS

Thermodynamics and Phase Equilibria
Chemical Kinetics and Catalysis
Chromatography
Optimization, Stability, and Process Control
Systems Analysis and Process Dynamics
Rheology and Fluid Mechanics
Polymer Science

BIOMEDICAL ENGINEERING

Blood Flow and Blood Trauma
Blood Pumping Systems
Biomaterials

Rice University

Rice is a privately endowed, nonsectarian, coeducational university. It occupies an architecturally attractive, tree-shaded campus of 300 acres, located in a fine residential area, 3 miles from the center of Houston. There are approximately 2200 undergraduate and 800 graduate students. The school offers the benefits of a complete university with programs in the various fields of science and the humanities, as well as in engineering. It has an excellent library with extensive holdings. The academic year is from August to May. As there are no summer classes, graduate students have nearly four months for research. The school offers excellent recreational and athletic facilities with a completely equipped gymnasium, and the southern climate makes outdoor sports, such as tennis, golf, and sailing year-round activities.

FINANCIAL SUPPORT

Full-time graduate students receive financial support with tuition remission and a tax-free fellowship of $333-400 per month.

APPLICATIONS AND INFORMATION

Address letters of inquiry to:

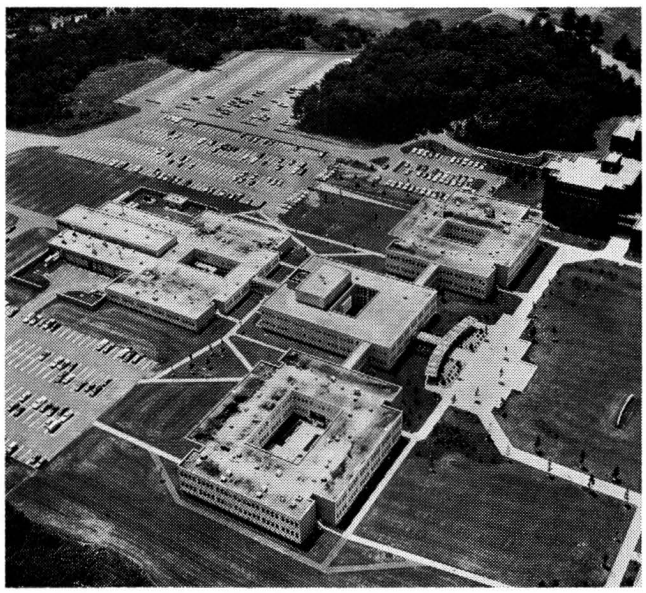
Chairman
Department of Chemical Engineering
Rice University
Houston, Texas 77001

Houston

With a population of nearly two million, Houston is the largest metropolitan, financial, and commercial center in the South and Southwest. It has achieved world-wide recognition through its vast and growing petrochemical complex, the pioneering medical and surgical activities at the Texas Medical Center, and the NASA Manned Spacecraft Center.

Houston is a cosmopolitan city with many cultural and recreational attractions. It has a well-known resident symphony orchestra, an opera, and a ballet company, which perform regularly in the newly constructed Jesse H. Jones Hall. Just east of the Rice campus is Hermann Park with its free zoo, golf course, Planetarium, and Museum of Natural Science. The air-conditioned Astrodome is the home of the Houston Astros and Oilers and the site of many other events.

RUTGERS THE STATE UNIVERSITY OF NEW JERSEY



College of Engineering

M.S. and Ph.D. PROGRAMS

IN THE DEPARTMENT OF

CHEMICAL AND BIOCHEMICAL ENGINEERING

AREAS OF TEACHING AND RESEARCH

CHEMICAL ENGINEERING FUNDAMENTALS

• THERMODYNAMICS • TRANSPORT PHENOMENA • KINETICS AND CATALYSIS • CONTROL THEORY, COMPUTERS AND OPTIMIZATION • POLYMERS AND SURFACE CHEMISTRY • SEMIPERMEABLE MEMBRANES

BIOCHEMICAL ENGINEERING FUNDAMENTALS

• MICROBIAL REACTIONS AND PRODUCTS • SOLUBLE AND IMMOBILIZED ENZYMES • BIOMATERIALS
• ENZYME AND FERMENTATION REACTORS

ENGINEERING APPLICATIONS

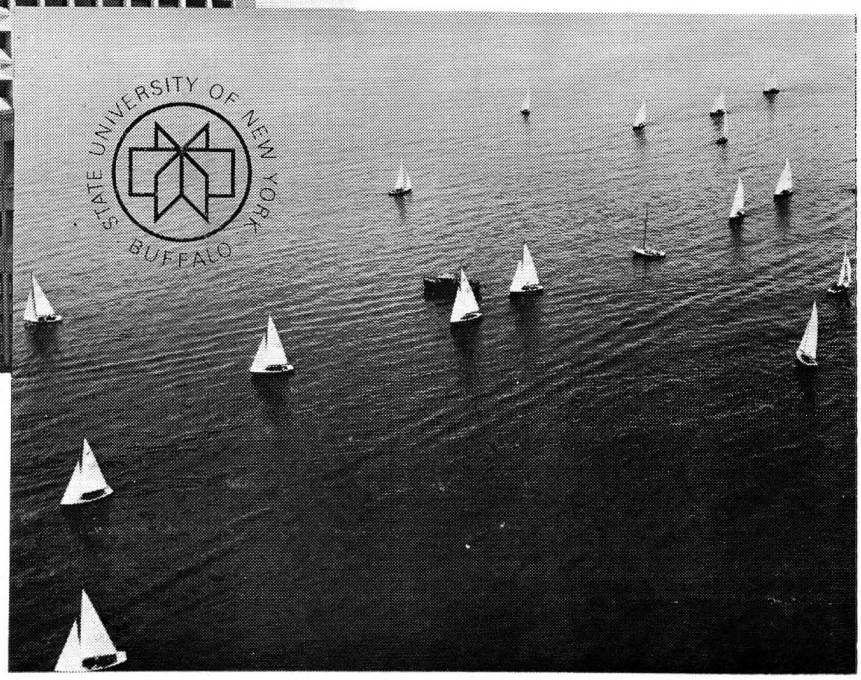
- BIOCHEMICAL TECHNOLOGY
  - INDUSTRIAL FERMENTATIONS
  - ENZYMES IN THERAPEUTIC MEDICINE, PHARMACEUTICAL PROCESSING AND WASTE TREATMENT
  - FOOD PROCESSING
- CHEMICAL TECHNOLOGY
  - FLAMMABILITY OF MATERIALS
  - PACKAGING
  - POLYMER PROCESSING
  - PLANT DESIGN AND ECONOMICS
- WATER RESOURCES ANALYSES
  - OCEANS AND ESTUARIES
  - QUALITY MANAGEMENT
  - WASTES RECOVERY

FELLOWSHIPS AND ASSISTANTSHIPS ARE AVAILABLE

For Application Forms and Further Information Write To:
Dr. A. Constantinides, Graduate Director
Department of Chemical and Biochemical Engineering
College of Engineering
Rutgers, The State University
New Brunswick, N.J. 08903

LOOK WHAT'S COMING TO BUFFALO!

The New Chemical Engineering Building
Clifford C. Furnas Hall



Sailing on nearby Lake Erie

The Department of Chemical Engineering at the State University of New York at Buffalo is proud to have the only State-supported chemical engineering program in New York. In the Fall of 1977, the Department will move into Furnas Hall on the new Amherst Campus on the outskirts of Buffalo. The building is ten stories and contains 75,000 square feet of offices and laboratories. This 1200-acre campus represents a $650 million investment in education. While it is part of a large university, Chemical Engineering at Buffalo is a highly personal educational experience.

RESEARCH

Energy Utilization
Environmental Problems
Kinetics and Catalysis

Process Design and Development
Biochemical Engineering

Fluid Mechanics and Rheology
Polymer Science and Engineering
Surface Science

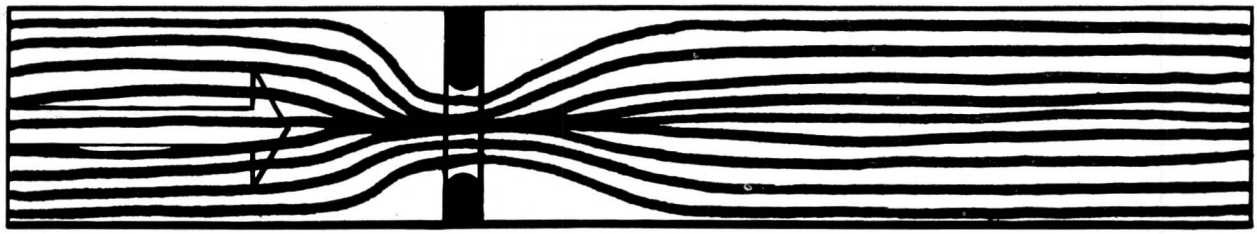
FACULTY

D. R. Brutvan	Staged operations
P. Ehrlich	Polymeric materials, thermodynamics
W. N. Gill	Dispersion, reverse osmosis
R. J. Good	Surface phenomena, adhesion
A. E. Hamielec (Adjunct)	Polymer synthesis and reactor engineering
K. M. Kiser	Blood flow, turbulence, pollution in lakes
P. J. Phillips	Polymer morphology, mechanical and electrical properties
M. Ryan	Polymer rheology, process optimization
E. Ruckenstein	Catalysis, interfacial phenomena, bioengineering
T. W. Weber	Process control, dynamics of adsorption
S. W. Weller	Catalysis, catalytic reactors
D. Zabriskie	Biochemical engineering, fermentation

Financial aid available for undergraduate and graduate students.

For further information please write or call me personally.

Dr. Sol W. Weller
Chemical Engineering Building
State University of New York
Buffalo, N.Y. 14214
(716) 831-3105



THE UNIVERSITY OF TENNESSEE

Graduate Studies in Chemical, Metallurgical & Polymer Engineering

Programs

Programs for the degrees of Master of Science and Doctor of Philosophy are offered in chemical engineering, metallurgical engineering and polymer engineering. The Master's program may be tailored as a terminal one with emphasis on professional dvelopment, or it may serve as preparation for more advanced work leading to the Doctorate.

Faculty

William T. Becker
Donald C. Bogue
Charlie R. Brooks
Duane D. Bruns
Edward S. Clark
Oran L. Culberson
John F. Fellers
George C. Frazier
Hsien-Wen Hsu
Homer F. Johnson, Department Head
Stanley H. Jury
Peter J. Meschter
Charles F. Moore
Ben F. Oliver, Professor-in-Charge of Metallurgical Engineering
Joseph J. Perona
Joseph E. Spruiell
E. Eugene Stansbury
James L. White

Research

Process Dynamics and Control
Sorption Kinetics and Dynamics of Packed Beds
Chromatographic and Ultracentrifuge Studies of Macromolecules
Development and Synthesis of New Engineering Polymers
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

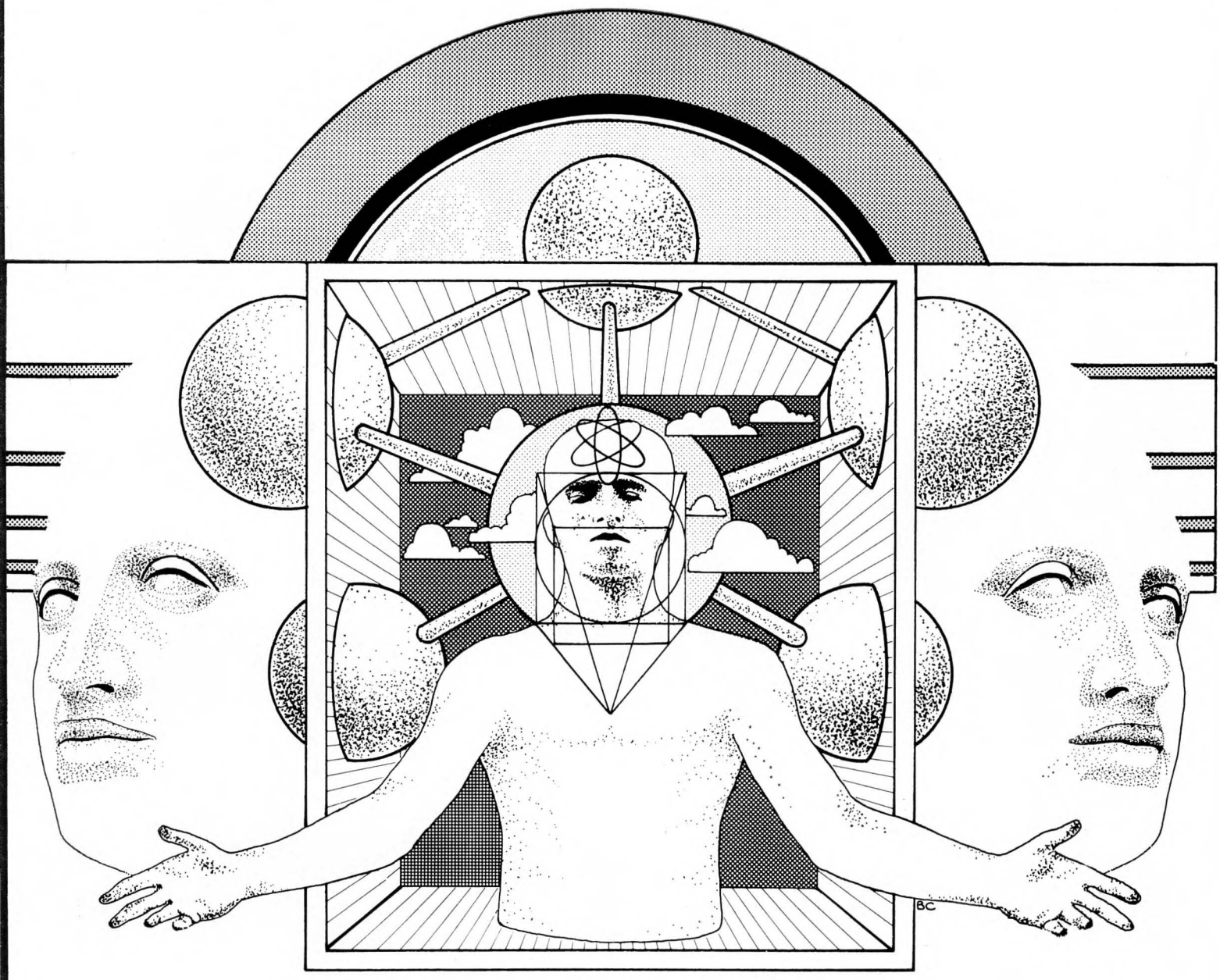
Sources available include graduate teaching assistantships, research assistantships, and industrial fellowships.

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

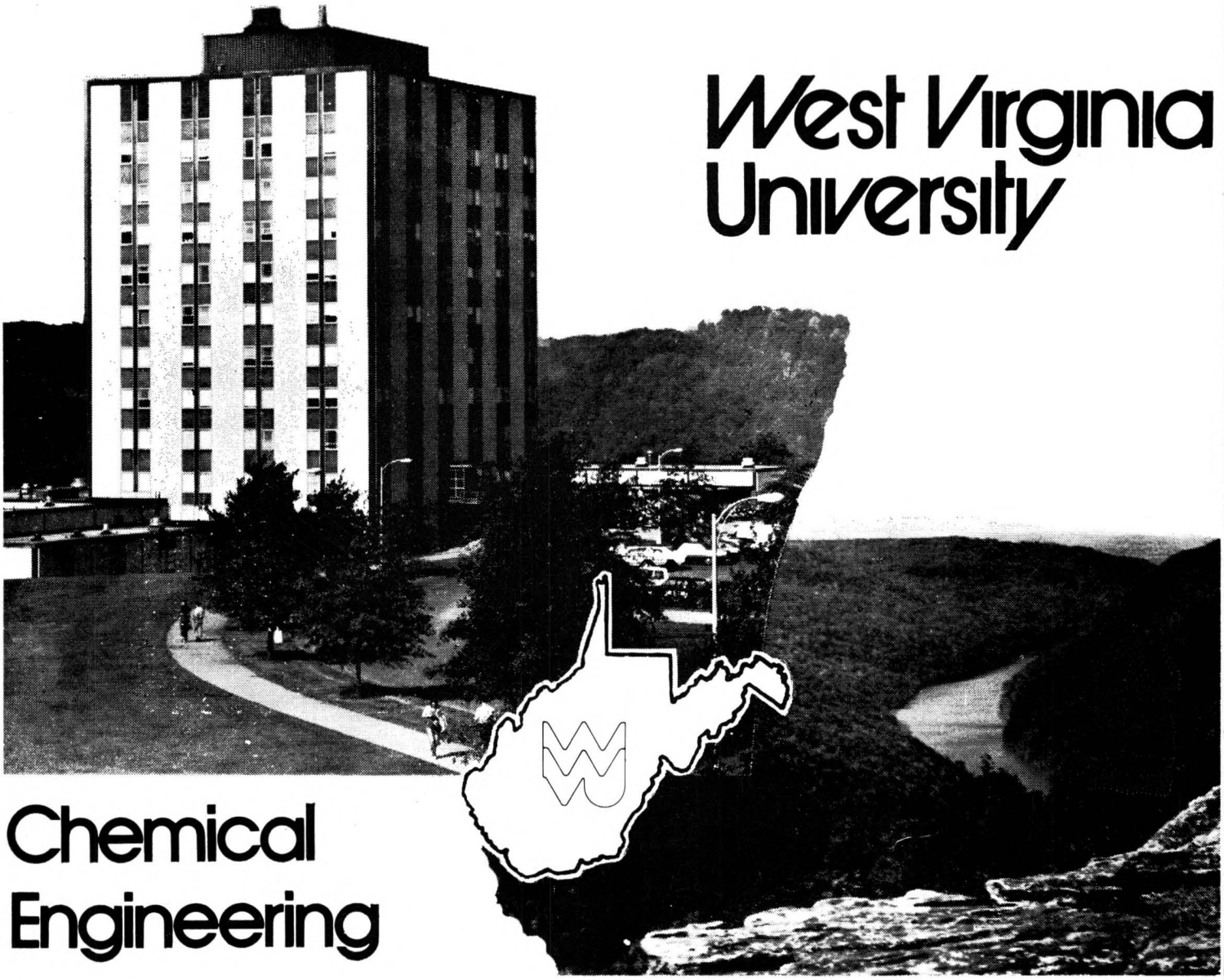
The Department offers a wide range of research topics for the creative student including:

- nuclear power engineering
- energy engineering, solar heating
- electrochemical engineering and corrosion
- polymer science and engineering
- plastics engineering and composite materials
- process modelling and optimal control
- fluid mechanics and pipeline transportation
- petrochemistry and tar sands development
- ceramics engineering
- 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
- SO_2 Scrubbing
- Economic Impact of Environmental Regulations
- River & Lake Modeling

Other Topics

- Optimization
- Chemical Kinetics
- Separation Processes
- Fluidization
- Bioengineering
- Transport Phenomena
- Utilization of Ultrasonic Energy

M.S. and Ph.D. Programs

For further information in financial aid write:

Dr. J. D. Henry
Department of Chemical Engineering
West Virginia University
Morgantown, West Virginia 26506

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
Edie, 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
Talbott, 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.

McMASTER UNIVERSITY

Hamilton, Ontario, Canada

M. ENG. & PH.D. PROGRAMS

THE FACULTY AND THEIR INTERESTS

R. B. Anderson (Ph. D., Iowa)	Catalysis, Adsorption, Kinetics
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 (PhD., 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

THE UNIVERSITY OF MICHIGAN
CHEMICAL ENGINEERING GRADUATE PROGRAMS on the ANN ARBOR CAMPUS

The University of Michigan awarded its first Chemical Engineering M.S. in 1912 and Ph.D. in 1914. It has moved with the times since and today offers a flexible program of graduate study that allows emphases ranging from fundamentals to design.

The Chemical Engineering Department, with 19 faculty members and some 70 graduate students, has opportunities for study and research in areas as diverse as: thermodynamics, reactor design, transport processes, mathematical and numerical methods, optimization, mixing, rheology, materials, bioengineering, electrochemical engineering, production-pipelining-storage of oil and gas, coal processing, and pollution control.

The M.S. program may be completed in 10 months and does not require a thesis. The Professional Degree requires thirty-hours beyond the Master's and a professional problem. The Ph.D. program has recently been revamped to expedite entry into a research area as early in the program as possible.

For further Information and applications, write:

Prof. Brice Carnahan
Chairman of the Graduate Committee
The University of Michigan
Department of Chemical Engineering
Ann Arbor, Michigan 48104

UNIVERSITY OF WASHINGTON Department of Chemical Engineering BF-10, Seattle, Washington 98195
GRADUATE STUDY BROCHURE AVAILABLE ON REQUEST

WASHINGTON STATE UNIVERSITY

Graduate Study in Chemical Engineering
M.S. and Ph.D. Programs

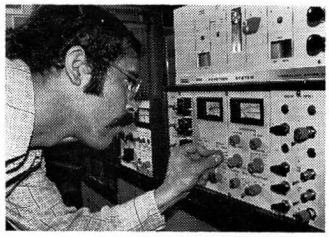
AIR POLLUTION:	Submicron Particulate Collection/High Temperature Catalysis/ Global Monitoring & Meteorological Interaction/Atmospheric Chemistry & Trace Analyses/ Odor Perception/Phytotoxicity
ENERGY:	Combustion & NO_x, SO_x Control/Coal Minerals Recovery/ Petrochemical Substitutes From Coal/Process Development & Design
TRANSPORT PHENOMENA:	Laser-Doppler Velocimetry/Single- & Multi-Phase Flow & Heat Transfer/ Foam Flow
NUCLEAR ENGINEERING:	Radioactive Waste Management/Fuels Reprocessing/LMFBR Technology/ Radiocarbon Dating/Neutron Activation Analyses
POLYMER ENGINEERING:	Electroiniated Polymerization/Polymeric Encapsulation
BIOMEDICAL ENGINEERING:	Biorheology
BIOCHEMICAL ENGINEERING:	Fermentation Kinetics

Several Fellowships, Assistantships and Full-time Summer Appointments Available

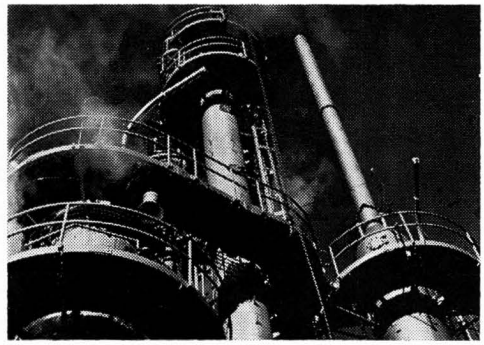
Contact: J. A. Brink, Jr., Chairman, Department of Chemical Engineering, Washington State University, Pullman, Wa. 99163/Tel. 509-335-4332.

Chemical Engineering Research at Merck
...Varied
...Challenging
...Significant

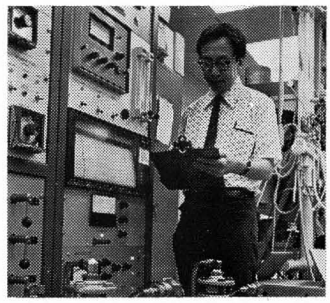
Carbon Adsorption Experiment



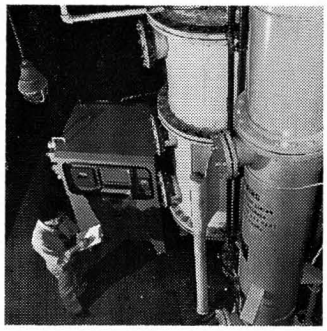
Micro-Reactor used in Heterogeneous Catalysis Studies



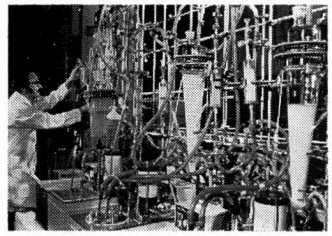
Rahway Plant
Chemical Manufacturing Unit



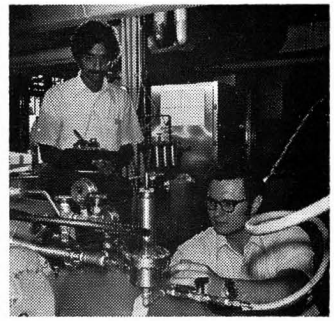
Computer Controlled Fermentor



Pilot Scale
Ion Exchange Columns



Continuous Separation of Optical Isomers via Selective Crystallization



Extraction Experiment
Antibiotic Solution

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For more details contact:
Manager, College Relations
Merck & Co., Inc.
Rahway, New Jersey 07065

"At Du Pont I work closely with control agencies to protect the environment."

—Sam Severance

Sam Severance is a BSChE from Georgia Tech and a member of Tau Beta Pi. Five years ago he joined Du Pont fresh out of school as an engineer. Now he's a Technical Supervisor in our Newark, N.J., Pigments Plant.

Sam and the people he supervises spend a full 30 per cent of their time working on environmental control, both in the plant and on effluent discharge systems outside the plant. As a result of this type of commitment, Du Pont has one of the best safety, health and environmental records in the industry.

This is typical of the kind of commitment Du Pont and its employees are making to improve the world we live in. And, Sam's story is typical of the progress Du Pont engineers, regardless of their degrees, can make for themselves, the Company and society.

So, if you'd like to work for a company that will permit you to make as big a contribution as you wish, do what Sam did. Talk with the Du Pont Personnel Representative who visits your campus. Or, write direct to Du Pont Company, Room 24764, Wilmington, Delaware 19898.

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