

GRADUATE EDUCATION ISSUE

MULTIVARIABLE CONTROL & ESTIMATION

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VIDEO-TAPED DATA ANALYSIS COURSE

Greenkorn & Kessler

CHEMISTRY OF CATALYTIC PROCESSES

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ENZYME & BIOCHEMICAL ENGINEERING

Tavlarides

SYNTHETIC & BIOLOGICAL POLYMERS

Thies

SOLID-STATE PROCESS TECHNOLOGY

Donaghey

COMPUTER PROCESS CONTROL

Corripio

WASTEWATER ENGINEERING

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SHERWOOD:

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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 schiils 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

Note to Department Chairmen, See Page 179.

**Fire Destroys
ChE Library**

Dear Sir:

Due to a fire, we lost our Chemical Engineering Building; the worst consequence was the loss of our library. The total losses are evaluated in the order of \$400,000. We have already received help from various departments of Chemical Engineering in our country and from U.S.A. as well.

This letter is to ask you to publish an appeal in CHEMICAL ENGINEERING EDUCATION to those departments of Chemical Engineering that might have books or journals which they'd be willing to donate. These would be most useful to our students and to our research staff.

Faculty of Engineering
National University of LaPlata
LaPlata, Argentina

**Compliments for
Carberry Commentary**

Dear Sir:

I just finished the Winter 1974 Issue of Chemical Engineering Education and felt compelled to compliment the authors of the sketch of Professor Carberry.

I thought it informative, as are most of your articles, but more importantly, it was good writing. In turn light and humorous and containing scholarly references, it presented a picture of a truly professional teacher who is clearly a man to be admired and respected. A good change from the dusty picture of a equally dusty professor.

Cordially,
R. J. Wall
Industrial Relations Administrator
Westvaco

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CHEMICAL ENGINEERING DIVISION ACTIVITIES

Twelfth Annual Lectureship Award to Elmer Gaden

The 1974 ASEE Chemical Engineering Division Lecturer was Dr. Elmer L. Gaden, Jr., of Columbia University. The purpose of this award lecture is to recognize and encourage outstanding achievement in an important field of fundamental chemical engineering theory or practice. The 3M Company provides the financial support for this annual lecture award.

Bestowed annually upon a distinguished engineering educator who delivers the Annual Lecture of the Chemical Engineering Division, the award consists of \$1,000 and an engraved certificate. These were presented to this year's Lecturer at the Annual Chemical Engineering Division Meeting June 28, 1974 at Rensselaer Polytechnic Institute, Troy, N.Y. Dr. Gaden spoke on "Biotechnology—An Old Solution to a New Problem."

Elmer L. Gaden, Jr., was born and raised in Brooklyn, New York. He attended the Polytechnic Institute of Brooklyn and transferred to Columbia University through enlistment in the naval training program of World War II. He graduated from Columbia during the war and later received the Ph.D. in chemical engineering from the same school.

Professor Gaden worked for Chas. Pfizer & Co., in biological process development, before returning to Columbia. He has had subsequent industrial experience with Biochemical Processes, Inc., a company which he founded and directed from 1958 to 1971, and with Radiation Applications, Inc.

With a primary technical interest in bioengineering, especially the analysis, design, and control of processes based on the activities of microbial populations, Professor Gaden has made important contributions to the understanding of aeration and oxygen transfer and to the kinetic relationships in such processes, microbial process design and control, and air sterilization by filtration. Dr. Gaden has also been the editor of the journal *Biotechnology and Bioengineering* since its inception. In 1970 he was the first recipient of the Food & Bioengineering Award of the AIChE.

Since 1949, Professor Gaden has been a member of the faculty at Columbia University with teaching responsibilities in chemical engineering, bioengineering, and, since 1966, history. He has also been responsible for initiating interdisciplinary undergraduate instruction in "technology and society." From 1960 to 1969 and again from 1971 he has been Chairman of the Department of Chemical Engineering and Applied Chemistry. In 1971 he received the Great Teachers Award and in 1973 the Harold C. Urey Award of Phi Lambda Upsilon.



PREVIOUS LECTURES

- 1963, A. B. Metzner, University of Delaware, "Non-Newtonian fluids."
- 1964, C. R. Wilke, University of California, "Mass transfer in turbulent flow."
- 1965, Leon Lapidus, Princeton University, "Aspects of modern control theory and application."
- 1966, Octave Levenspiel, Illinois Institute of Technology, "Changing Attitudes to Reactor Design."
- 1967, Andreas Acrivos, Stanford University, "Matched Asymptotic Expansions."
- 1968, L. E. Scriven, University of Minnesota, "Flow and Transfer at Fluid Interfaces."
- 1969, C. J. Pings, California Institute of Technology, "Some Current Studies in Liquid State Physics."
- 1970, J. M. Smith, University of California at Davis, "Photo chemical Processing—Photo Decomposition of Pollutants in Water."
- 1971, William R. Schowalter, Princeton University, "The Art and Science of Rheology."
- 1972, Dale F. Rudd, University of Wisconsin, "Synthesis and Analysis Engineering."
- 1973, Rutherford Aris, University of Minnesota, "Diffusion and Reaction in Porous Catalysts—a Chemical Engineering Symphony."

DIGITAL COMPUTER CONTROL OF PROCESSES

ARMANDO B. CORRIPIO
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Baton Rouge, Louisiana 70803

COMPUTER PROCESS CONTROL, as space travel, is no longer a dream but a reality. The time when every new plant of significant size will be equipped with a control computer is rapidly approaching. Recognizing this fact the Department of Chemical Engineering at LSU initiated six years ago a course on the use of digital computers in process control. This graduate course is one of four offered by the department in the area of automatic process control:

Course Title	Level
Introduction to Automatic Control Theory	Senior/Graduate
Process dynamics and adaptive control	Graduate
Optimal control of processes	Graduate
Digital Computer Process Control	Graduate

The first of these courses is a pre-requisite to the other three which are independent of each other. Each of the graduate courses covers different aspects of modern control theory with actual or potential application to chemical processes. As

Computer process control, like space travel, is no longer a dream but a reality; the time when every new plant of significant size will be equipped with a control computer is rapidly approaching.

a matter of historical interest, two of these courses were initiated over two decades ago by the late Arthur G. Keller, as survey courses in process instrumentation and control.

The objective of the course is to familiarize the student with the control capabilities of the digital computer and with the techniques he will need to design the control routines to be executed by the computer. The course outline given in Table I is a list of the topics covered.

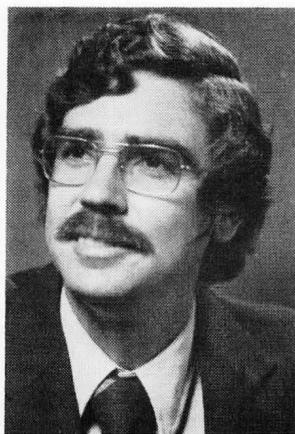
Table I
COURSE OUTLINE

- I. Introduction
 1. Review of automatic process control theory
 2. Description of the computer hardware necessary for real-time operation
 3. Programming the computer for real-time operation
 4. Economic justification
- II. Design of Sampled-Data Control Systems
 1. The algebra of z-transforms
 2. Stability of sampled-data systems
 3. Effect of noise and digital filtering
- III. Feedback Control Algorithms
 1. Synthesis of control algorithms
 2. Discrete equivalent of standard two- and three-mode controllers
 3. Process models and tuning techniques
 4. Effect of sampling interval
- IV. Advanced Control Techniques
 1. Feedforward control
 2. Cascade control systems
 3. Interaction index and decoupling of multi-variable systems
 4. On-line identification and adaptive control
 5. Compensation of transportation lag
- V. Optimization of Process Operation
 1. Formulation of the optimization problem and the performance index
 2. Linear programming and constrained optimum
 3. On-line search methods

CONTROL LOOP ANALYSIS

A REVIEW OF AUTOMATIC control theory is given in the form of an analysis of the different components of the typical control loop. Special attention is devoted to the conventional two- and three-mode analog controllers for later comparison with the digital version of the feedback controller. As part of the introduction the student, who is usually familiar with programming the computer for "batch" solution of scientific problems, is exposed to the special hardware and programming considerations required for "real-time" operation, i. e. continuous attention of a process that takes place in actual time. The significant factors involved in economically justifying a computer in a process control application are also presented.

The course as taught at LSU uses z-transform



Armando B. Corripio is Assistant Professor of Chemical Engineering at Louisiana State University, Baton Rouge, Louisiana. He attended the University of Villanueva in Havana, Cuba until closed by the Castro regime in April 1961, on the day of the Bay of Pigs invasion. He holds B.S. (1963), M.S. (1967) and Ph.D. (1970) degrees in Chemical Engineering, all from L.S.U. His industrial experience includes five years of process simulation and control systems design with Dow Chemical Company. Member of AIChE, ISA, SCS and COED, his main interest lies in the areas of computer simulation and automatic control theory. He is author or co-author of over thirty articles and presentations, is married and has four children, ages 1, 7, 9 and 10.

algebra as a tool in the analysis of the sampled-data control loop, and in the synthesis of digital control algorithms. Pulse transfer functions and their use in the determination of the stability of the loop are given particular attention, as are the most common forms of data holds on the computer output signals. The effect of noise on the sampling process and its attenuation by digital filtering are also presented.

The synthesis of digital control algorithms is illustrated by the presentation of the deadbeat, Dahlin and Kalman algorithms. These algorithms will, under certain conditions, cause excessive switching of the control valve, a phenomenon known as "ringing". As a result of a term project assigned to one of the students in the course, a demonstration of ringing utilizing the Chemical Engineering Hybrid Simulation Laboratory has been developed. The demonstration consists of a continuous stirred tank chemical reactor, simulated on the analog computer and controlled by the digital computer through the hybrid interface. (See Table II). Given this set-up the student is able to obtain a model of the process, synthesize a digital control algorithm which is programmed on the digital computer, and observe the effect of ringing. He is also able to identify and remove the ringing poles in the control algorithms and observe the performance of the

Table II

HYBRID COMPUTER HARDWARE

Analog Computer

Electronic Associates Model 680
 75 operational amplifiers
 30 integrator/summer networks
 20 multipliers/square/square-root cards
 2 adjustable function generators
 Assorted parallel logic: AND gates, FLIP FLOPS, etc.

Hybrid Interface

Electronic Associates Model 693
 24-channels of analog-to-digital conversion
 12 channels of digital to analog converters
 16 digital output lines (logic levels)
 8 digital input lines (logic levels)
 6 interrupt lines

Digital Computer

Xerox Model Sigma-5
 20,000 words, 32 bits per word
 Hardware floating-point unit
 750,000 bytes of bulk storage (disk)
 Card reader
 Line printer
 Operator's console
 6 levels of priority interrupt

Software

Sigma Macro-symbol assembler
 FORTRAN compiler
 SL-1 Simulation Language
 Hybrid subroutine package (FORTRAN callable)

A demonstration of ringing using the ChE Hybrid Simulation Lab has been developed. It consists of a continuous stirred tank chemical reactor simulated on analog computer, controlled by digital computer through hybrid interface.

"ringing-free" algorithm. The set-up can also be used to test the different methods of obtaining simple models of a process, and to observe the effect of varying the computer sampling interval.

OBSERVING COMPUTER RESPONSE

MANY OF THE INDUSTRIAL applications of digital control computers involve the use of discrete equivalents of the conventional analog two- and three-mode controllers. A number of methods to tune the parameters of the analog controllers have been adapted to their digital counterparts. These include Zeigler-Nichols, Cohen and Coon, and a number of empirical formulas de-

(Continued on page 203.)

PROCESS TECHNOLOGY OF SOLID-STATE MATERIALS AND DEVICES

LEE F. DONAGHEY

*University of California, Berkeley
Berkeley, Calif. 94720*

THE CHEMICAL ENGINEER is making an increasing number of contributions to solid state industries, from ultrapurification and single crystal production to process engineering in semiconductor integrated electronics. The rapidly-evolving technological requirements of the highly competitive electronic materials and device industries are creating new horizons for well trained chemical engineers with specialization in solid state engineering: a working knowledge of solid state chemistry, basic device physics and process chemical engineering. In response to the importance of contributing to solid state engineering education, a new course has been introduced into the chemical engineering curriculum at the University of California, Berkeley.

The foundations of the modern solid state industries developed slowly in the early 1900's. Among the most important concepts was that of crystal lattice defects introduced by Frenkel in 1926. Schottky and Wagner, Fowler and others then developed the statistical mechanics of crystals to describe states of disorder in a nearly perfect lattice. Wilson also contributed to this development with the band theory of solids which was based on quantum mechanics. The recognition of the importance of defects in solids has had a profound influence on our current understanding of many diverse phenomena including solid state reactions, heterogeneous catalysis, semiconductor electronics, photography and laser physics. The defect chemistry of solids is of such continuing importance in solid state engineering that this subject, including the supporting basics of solid state chemistry were chosen for the basis of the new course.

The beginning of electronic device technology began in earnest with the disclosure of the Schottky-barrier field-effect transistor in 1940. At



Lee F. Donaghey received the B.A. degree in Physics from Harvard College, and the M.S. and Ph.D. degrees in Materials Science from Stanford University. His industrial experience has been in the semiconductor and microwave electronics industries. Following a postdoctoral appointment at the Royal Institute of Technology, Stockholm, he joined the Chemical Engineering faculty at the University of California, Berkeley in 1970. His research interests are concerned with the synthesis, thermochemistry and process kinetics of electronic materials.

that time the device operated at a net power loss, and it was evident that new experimental technologies were needed for ultrapure single crystal production and device processing. New purification procedures such as zone refining were introduced, as well as techniques able to control surface defects. The new approaches ultimately climaxed in power gain with the Bardeen-Brattain point contact transistor in 1947. Since that time advancements in process technology of solid state devices have appeared at an ever accelerating rate. In recent years, planar processing, large scale integration, and single crystal film processing have expanded the techniques and needed expertise of the process engineer. The basis for understanding these developments in process technology, and techniques for applying them in current applications, form the latter part of the new course.

COURSE OBJECTIVES

THE MAIN PURPOSE of this course then is to provide students with an introduction to and working knowledge of (a) the chemistry of the solid state, (b) theory and practice of single crystal growth and (c) process operations and technologies for solid state device fabrication. An important theme is that the attainable physical properties of electronic, magnetic and optical materials are often limited by process-induced defects, and as a consequence, fabrication processes must be designed to control materials properties so as to optimize the performance of the final device. The student acquires an understanding of the methods for control of electrically, magnetically and optically active defects and gains insight into the effect of processing variables on materials and defect-related device properties.

The course is a chemical engineering elective designed for senior and first year graduate students of chemical engineering who are interested in a materials engineering option. Nevertheless, this one-quarter course has attracted students from departments of electrical engineering, chemistry and materials science. A prerequisite for enrollment is a basic course in materials science or materials engineering; most of the chemical engineering seniors at Berkeley, and many entering graduate students have completed this prerequisite. In addition, some chemical engineering students concurrently enroll in an electrical engineering course in Electronic Circuits designed specifically for non-majors.

The new course complements several electronic materials and related curricula within the university. The chemical engineering courses in Mass Transfer, Transport Phenomena and Chemical Processing of Inorganic Compounds coordinate with the sections on crystal growth, chemical vapor deposition, oxidation and diffusion. The course treatment of silicon is extended in the electrical engineering courses Processing and Design of Integrated Circuits, and Semiconductor Devices; also, the treatment of point defect thermodynamics provides a basis for advanced physical property studies offered in Physics and Chemistry of Semiconductors. Two complementary courses in physical properties are offered in materials science: Thermal and Optical Properties of Materials and Electrical and Magnetic Properties of Materials. Nevertheless, the treatment of the defect chemistry of solids and rela-

Table I.

OUTLINE OF COURSE ON ELECTRONIC MATERIALS

	Ref.
1. Introduction: Solid-State Engineering; Materials and Devices; Process Technologies.	1, 2
2. Crystal Chemistry: Crystal Structures and Bonding; Energetics of Defects; Point Defect Equilibria; Laser Crystal Chemistry.	1, 3-5
3. Electronic Defect Structure: Equilibria with Impurities; Transport Properties and Lattice Defects.	1, 3, 4
4. Ultrapurification: Purification Schemes; Halide Transport; Zone Refining.	6, 7, 8
5. Crystal Growth: Use of Phase Equilibria; Czochralski Crystal Growth; Growth from Solution.	1, 9, 10
6. Chemical Vapor Deposition: Kinetic Mechanisms; Chemical Transport; Vapor Phase Epitaxy of Silicon and Gallium Arsenide-Phosphide.	11, 12
7. Processing of Silicon Devices: Photoresist Technology; Chemical Etching; Oxidation; Diffusion.	2, 11
8. Discrete Component Processing: MOS Technologies; Packaging.	11, 13
9. Electro-optical Device Processing: Solar Cells; Light-Emitting Diodes; Heterostructure Devices.	14, 15
10. Magnetic Device Processing: Magnetic Thin Films; Garnet Film Memories.	16, 17

The main purpose of the course is to provide a working knowledge of solid-state chemistry, theory and practice of single crystal growth and process operations and technology for solid state device fabrication.

tion to chemical phenomena in solid state materials and device processing remains unique to the new course.

COURSE CONTENT

THE TEN TOPICAL sections shown in Table I comprise the course content. The student is introduced to the field of solid state engineering and shown how materials purification, crystal growth and select processing steps influence the performance of solid state devices. Single crystals and working devices serve as in-class examples: 3" dia. germanium crystals, ultra-high purity compound crystals, and silicon memory chips, light-emitting diodes and magnetic thin film memories in different stages of fabrication.

The fundamentals of crystal chemistry are explored in the next section beginning with a review of Bravais lattices and bonding. Magnetic and ferroelectric crystal structures are examined from an ion-centered approach, while optical, semiconducting and superconducting crystals are examined in terms of bonding and band structure. Defects in solids are introduced, and mass action relations between point defects solved by matrix methods to obtain defect equilibria. Factors influencing substitutional ion solubilities in laser crystals are explored. Defect equilibria between electronic defects and impurities are then introduced and related to electronic transport properties.

Section four presents ultrapurification schemes for elements and compounds. The selected removal of electrically active impurities is emphasized. Two purification processes are examined in detail: halide transport purification and zone refining, using a case study approach for silicon and group III-V compounds.

Crystal growth fundamentals are presented in Section five, where phase equilibrium requirements and non-stoichiometry consequences are explored for different growth methods. Interface attachment kinetics and defect densities are related to crystallization driving forces for different growth mechanisms. Czochralski crystal growth of silicon and III-V compounds and solution

are explored. An illustrative problem treated is described in Homework Example 2.

Section seven is devoted to unit processes for solid state device fabrication. For several processes, chemical etching, oxidation and diffusion, there exists a wealth of literature, and easily identified rate dependence on lattice defects. Consequently, these processes serve to exemplify the influence process variables have on physical properties of solid state materials.

In Sections eight through ten, process technologies of selected devices are presented: bipolar and metal-oxide-silicon (MOS) transistors, solar cells and light-emitting diodes and magnetic thin film memories. For each, the sequence of process operations is identified and the process conditions and critical properties are outlined. The unit processes examined earlier in the course are drawn on as a basis for this section. In homework problems the processing conditions needed to achieve a final device of given characteristics are sought in terms of rate processes and process alternatives.

Demonstrations supplement the lecture and reading material, and provide closer contact with industrial processes.* Czochralski crystal growth is demonstrated, and melt convection simulated. Chemical vapor deposition is demonstrated with a graduate research reactor. The current-voltage characteristics of electronic devices are demon-

The rapidly evolving technological requirements of the highly competitive electronic materials and device industries are creating new horizons for well-trained chemical engineers with specialization in solid state engineering: a working knowledge of solid state chemistry, basic device physics and process ChE.

growth of garnets are treated as extended examples. Interesting interactions are explored between crystal growth phenomena and lattice defects which influence both impurity solubility and growth rates. A typical problem is shown in Homework Example 1.

Reactor design and chemical reaction processes of chemical vapor deposition are presented in Section six, beginning with a discussion of kinetic mechanisms and rate control regimes. Closed system chemical transport crystal growth fundamentals are explored. Finally, commercial reactors, chemical reactions and growth conditions for silicon and gallium arsenide-phosphide

strated with a semiconductor curve tracer.

A term paper was an integral part of the course during the first two years of development. This project served to integrate the course material with a specific topic of interest to each student. The conditions and deadlines for this assignment were presented at the beginning of the course, with a topic approved and abstract written by mid quarter. The most successful topics chosen are listed in Table II. In the last

*Supported in part by the U. S. Atomic Energy Commission through the Inorganic Materials Research Division of the Lawrence Berkeley Laboratory.

Table II.

TERM PAPER TOPICS

- MOS Processing Techniques.
- Ion Implantation Techniques for the Manufacture of New Semiconductor Devices.
- Recent Innovations in Zone Refining.
- Photoresist Properties and Use in Semiconductor Processing Operations.
- Light Emitting Diode Processing.
- Laser Crystals: How they work and Some Preparative Methods.
- Modification of Solvent Compositions for Liquid Phase Epitaxial Growth of Magnetic Thin-Film Garnets.

year, this assignment was omitted to allow greater development of device process technologies with illustrative, extended homework assignments.

There exist no comprehensive text able to cover the broad subject matter treated in the course. Consequently, an extensive set of course notes is provided. The book **Solid-State Chemistry** by Hannay¹ has served as an introductory text, with reading assignments drawn from the reference list. Slides are used as a part of many lectures to present examples from the reading. Although the course material appears extensive, experience has shown that well directed homework and reading assignments enable the conscientious student to handle the material without difficulty.

SUMMARY

IN THE THREE YEARS during which this course has been given the emphasis has expanded from the fundamentals of solid state chemistry and control of electrically active defects toward a fuller explication of unit processes and technologies for currently important electronic devices such as bipolar and MOS integrated circuits, light-emitting devices, and "bubble domain" magnetic memories. Whereas the former emphasis is more important for materials engineers, this subject causes chemical engineers the most difficulty. The exploration of basic processes such as crystal growth, oxidation and diffusion provides students with a better understanding of the effect of process variables on defect-related physical properties. Coverage of the process technologies for specific solid state devices tends to kindle the most interest and is more important for preparing chemical engineers for roles in solid state industries. Many alumni of this course have

already launched successful careers in local electronics and solid state materials industries, where the demand for the chemical engineer with specialized skills in materials is increasing. □

HOMEWORK EXAMPLE 1:

Neodymium Distribution in Czochralski Grown CaWO_4

The addition of Na_2O to the melt significantly affects the solubility of Nd^{3+} ions in CaWO_4 through charge compensation with Na^+ ions. In this problem the distribution of Nd^{3+} along a CaWO_4 crystal grown by the Czochralski method is to be calculated from distribution coefficients for Nd and Na and from properties of the diffusion boundary layer at the crystallizing interface. The instantaneous ion concentrations in the crystal are calculated by solving mass action relations for Schottky defect formation, Nd substitution on a Ca site with Ca vacancy formation, Na substitution on a Ca site with formation of an oxygen vacancy, and the time-dependent Na_2O and Nd_2O_3 concentrations in the melt. This problem demonstrates the interdependence of defect mass action relationships with crystal growth conditions.

HOMEWORK EXAMPLE 2:

Chemical Vapor Deposition of $\text{GaAs}_{1-x}\text{P}_x$

Phase equilibrium temperatures and deposition rates are explored within a barrel reactor in which gallium arsenide-phosphide solid solutions are deposited from GaCl , As_2 , P_4 and HCl source vapors transposed by H_2 . The vapor-solid reaction equilibria are solved simultaneously to deduce the equilibrium temperature and solid solution composition for the overall reaction. Side reactions are omitted in this simplified analysis. The deposition rates at lower temperatures are determined by solving the set of component molar flux equations for a film boundary layer. This problem provides useful criteria for understanding commercial reactors for electro-optical film deposition.

REFERENCES

1. N. B. Hannay, *Solid-State Chemistry*, Prentice-Hall, Inc., Englewood Cliffs, N. J., 1967.
2. D. Baker, D. C. Koehler, W. O. Fleckenstein, C. E. Roden and R. Sabia, *Physical Design of Electronic Systems*, Vol. 3, *Integrated Device and Connection*

(Continued on page 198.)

MULTIVARIABLE CONTROL AND ESTIMATION

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IN THE 1970 Graduate Education Issue of *Chemical Engineering Education*, Lowell Koppel lamented that advanced control techniques had not been considered to be practical or effective in spite of the significant number of engineers with graduate level training in process control. Today, however, it appears that there is a real opportunity for advanced control techniques to have a significant impact on the practice of process control in the chemical industry. Concomitantly, graduate education in control theory can contribute to the emergence of the new control methods.

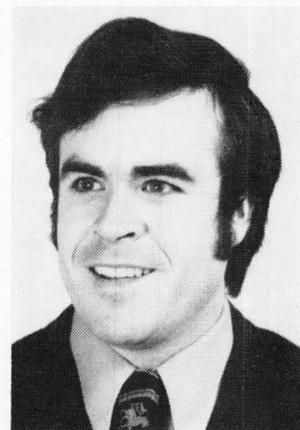
Let us examine the current situation in more detail. First, the dedicated process computer has been made a reality via the development of inexpensive process control software and hardware. Second, some of the ideas which have received theoretical attention in the control literature have now been subjected to experimental verification. For example, the increase in effectiveness of multivariable control, where the controller is fed information from all outputs, over single loop control (single measurement feedback) has been clearly demonstrated by several investigators^{1, 2}. Third, increased energy costs have caused supervisory personnel to re-examine the economic trade-off between energy consumption and product specifications, both for steady state and dynamic operation. Fourth, the use of the computer for data acquisition and supervisory control as well as in single loop DDC has been accepted in the process industries—a development which clears the way for further advances in sophistication.

Given the current industrial situation, how does one attempt to structure the graduate curriculum in control so that it will present the important concepts but also eventually have some impact on control practice? There are a number of relevant facts to consider here:

- Today there are fewer graduate students specializing in process control, most of them M. S. candidates with relatively short holdup times. This situation together with faculty logistics usually permit the offering of only one graduate control course.

- A chemical engineering graduate course in control should not and need not duplicate other engineering control courses. It should emphasize theory and application indigenous to the chemical process industry.

- Since a classical control course based on frequency domain analysis is traditionally taught undergraduates, the graduate course should interface with that background. In order to communicate with a practicing control engineer, the graduate must be able to speak in terms of transfer functions and PID controllers. Unfortunately these subjects have not been addressed in most advanced control theory books based on time domain analysis.



Tom Edgar is an assistant professor at The University of Texas at Austin. He came to Texas from Princeton University (Ph.D. 1971), where he specialized in control theory and collision and trajectory analysis, the latter two topics mainly applied to intercollegiate competition in rugby and volleyball. His B.S. degree is from the University of Kansas, and he has worked as a process engineer for Continental Oil Company. At Texas he is engaged in teaching and research in the fields of multivariable control, optimization, process modeling, and energy systems.

- Experimental computer control facilities, if available, should be integrated into the control course. This is the surest way to lend credibility to advanced control concepts. The 1970 survey of universities by the CACHE Real-Time Task Force has shown that nearly fifty chemical engineering departments had acquired or were planning to acquire computers for use in their laboratories.

COURSE PEDAGOGY

GIVEN THE ABOVE considerations, the graduate offering in modern control theory at the University of Texas has evolved into a course on multivariable control and estimation. The course emphasizes the development of control strategies based on state variable models but not necessarily limited to the use of optimization theory. The concepts of transfer functions, both continuous and discrete, are introduced, and the design of feedback control laws for single input-single output systems is shown to be a subproblem of the multiple input-multiple output design problem. The majority of the course material is based on linear(ized) systems, for which many useful mathematical results have been developed.

Coverage of basic mathematical concepts, especially those of static optimization and matrix techniques, is minimized in the interests of time. Variations in the mathematical background of the students can be rather wide, but it has been found that most students will accept the scale-up of a two dimensional example to a matrix expression. By later studying a higher order example, they do obtain an appreciation for the power of matrix notation.

An important ingredient of the course is the providing of experience via computer simulation and real-time computer control experimentation. The experiments require knowledge of computer programming (Fortran, Basic); however, the student does not need to learn details on instrumentation or computer hardware although that option is available.

As part of a large project on computer-based education at the University of Texas, modularizing of certain portions of the course has been attempted to strengthen the learning process, with good success. A module consists of explanatory material (both theory and application) on a specific topic in which the student behavioral objectives or goals are clearly defined by the in-

structor. The student then proceeds to independently learn the concepts via conjunctive use of textbooks and material written by the instructor. Study questions are used to reinforce the understanding of the module. By formulating the module as a project with many options and alternatives and requiring the student or group of students to write a report on their results, the students' creativity in thought and expression is stimulated. This procedure along with several examinations indicate whether the student has

... modularization of certain portions of the course has been attempted to strengthen the learning process, with good success... student evaluation has shown that this definitely enhances the quality of the course.

attained the desired behavioral objectives. If the students do not learn the specific concepts, then the module should be altered so that they do. Modules also provide additional experience in independent study; the capacity for self-study is a valuable trait for continued professional development.

Student evaluation of the module approach has shown that it definitely enhances the quality of the course. The mathematics of modern control theory are rather difficult to master, and supplementary information as well as study questions on the various subjects prove to be helpful. The modules can sometimes stand in place of a lecture; less than twenty percent of my lectures have been displaced by this medium. In those cases the lecture time is used for informal discussion of the concept or experiment under study. The transferability of a module to another school is another important consideration, and great care has been exercised to design the modules so that they could be implemented elsewhere.

COURSE CONTENT

A GENERAL OUTLINE of the course is given in Table I. A heavy emphasis is placed on linear system theory, both for control and estimation, since these topics have a much higher probability of near-term application in the chemical industry.

Table I
COURSE OUTLINE

- I. Review of Static Optimization
- II. State Representation of Dynamic Systems
 - A. State Equations
 - B. Eigenvalues, Modal Analysis, Modal Control
 - C. Controllability, Observability
- III. Dynamic Optimization—Continuous Time
 - A. The Variational Approach
 - B. The Linear Quadratic Problem (LQP)
 - C. Constrained Control, Minimum Time Control
 - D. Nonlinear System Control
- IV. Dynamic Optimization—Discrete Time
 - A. State Equations
 - B. Discrete Dynamic Programming—LQP
- V. State and Parameter Estimation
 - A. Observer Theory
 - B. Kalman Filtering
 - C. Nonlinear System Estimation

Modules have been written on the following subjects:

IIB: modal analysis and control

IIIB: optimal multivariable control of a distillation column

IIIC: minimum time control of linear systems (phase plane analysis)

V: sequential parameter estimation in a stirred tank

The parameter estimation module has been used with real-time computer data acquisition and computation, while the other modules have used simulation (digital and analog) for demonstrating the concepts. Equipment limitations have previously prevented the application of actual experimentation to the first two modules, but this problem has recently been resolved.

The textbook used is *Modern Control Engineering* by Maxwell Noton; the text more or less covers the topics listed in Table I. The book

The course emphasizes the development of control strategies based on state variable models but not necessarily limited to use of optimization theory . . . an important ingredient is providing experience via computer simulation and real-time computer control experimentation.

is interdisciplinary in its presentation, although not as extensive in scope as those books used for additional study in the course³⁻⁸. After a short review of static optimization using the book, the study of linear continuous system dynamics is undertaken. Such subjects as eigenvalues/eigenvectors and their relationships to transient re-

sponse, canonical forms, state variable notation, multivariable Laplace transforms, the transition matrix, and the modal equations⁹ are presented here.

At this point the student is prepared for the first application of multivariable control. Proportional control of the states is assumed to be the most practical strategy for process regulation. It can be easily shown that the addition of feedback control in effect shifts the eigenvalues of the open-loop model. The proposed controller should realize a quick-responding closed-loop system where the eigenvalues have large negative real parts. Thus the so-called pole placement or modal control technique offers one multivariable control approach. One can adjust the elements of the feedback matrix, K , to obtain the desired closed loop behavior. This can be done intuitively, by optimization techniques, or by other methods^{9, 10, 11}. The students are cautioned, however, that the system eigenvectors can cause unpredictable behavior. These factors are studied in the first module.

TYPICAL PROBLEM

A PILOT SCALE distillation column system in the laboratory can be introduced at this juncture as a typical multivariable control problem. Since most multivariable systems are derived from physical principles (black box multivariable modeling techniques are not yet well-developed), this approach is used for the column model development. The Huckaba model¹² for a column with n trays and reboiler and condenser yields a set of $n + 2$ nonlinear ordinary differential equations. The derivation is explained in detail in a student handout. This model has been experimentally verified and thus assumes some credibility. By linearizing the equations, a state space model of the form,

$$\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu} + \mathbf{Cd}$$

is derived, where \mathbf{x} , \mathbf{u} , and \mathbf{d} are the state, control, and disturbance vectors. This system can be used as the focus of various linear multivariable control strategies, such as the modal control technique mentioned above.

The second major approach for design of multivariable controllers utilizes the the minimum principle applied to the linear state equation with quadratic objective function, the well-known linear-quadratic problem (LQP). The basic optimal control structure for the LQP is linear feed-

back; if the disturbance, d , is non-zero, the LQP solution consists of proportional feedback plus feedforward control. Thus the notion of feedforward control to anticipate the effect of the disturbance, a concept which is now well-established in control practice (via transfer function analysis), arises in optimal multivariable control. By proper choice of the objective function,

One of the more interesting applications is the control of a fluid catalytic cracker system . . . the distributed parameter version of the LQP is briefly treated in class by discretization of the spatial variable—"if you don't like it, lump it."

an optimal PID controller can be computed. For simple systems this correlates closely with the PID controller tuned using classical control theory.¹³ Optimal control theory clearly demonstrates the effect of the integral model; it only makes the controller more sluggish, but its advantages include compensation for model errors and the smoothing of the control action.

The computation of multivariable control via the LQP is rather straightforward, and there are "canned" computer programs available for controller design. Such a program, VASP¹⁴ (Variable Dimension Automatic Synthesis Program), links available Fortran subroutines (e. g., integration of Riccati equation, formation of transition matrix, etc.) and requires a minimum of programming effort, thus permitting the student to concentrate on the interpretation of his results. In the second module the student applies the LQP computation to the distillation column model. The articles on optimal feedforward/feedback control by Hu and Ramirez¹⁵ and Newell et al.¹ serve as good supplementary papers.

THEORY VERSATILITY

EXTENSIONS AND APPLICATIONS of the LQP are also discussed. The recent survey article by Edgar et al.¹⁶ has reviewed the versatility of LQP theory and its applications; one of the more interesting applications is the control of a fluid catalytic cracker system.¹⁷ The distributed parameter version of the LQP is briefly treated in class by discretization of the spatial variable ("if you don't like it, lump it"). The discrete

version of the LQP is solved using discrete dynamic programming, which permits the discussion of Bellman's principle of optimality. The discrete LQP is discussed in conjunction with digital control, and the conversion from continuous time to discrete time and the definition of discrete state variables are covered here.

In the third module the subject of continuous time dynamic optimization is continued with discussions of the linear minimum time problem and various algorithms for solving it. Phase plane analysis is an important tool for understanding control synthesis, and real-time simulation of the phase plane on an analog computer readily shows how difficult it is to perform minimum time control. While minimum time control is open loop control, it does exhibit a multivariable feedback nature in that a switching function based on the adjoint variables is defined via the minimum principle.

The final section of the course is state and parameter estimation. This area is relatively difficult for the student because of the need to use probability theory. For no noise in the system, the Luenberger observer is used; for noisy systems, the Kalman filtering algorithm must be introduced. In order to show how a simple sequential linear least squares algorithm is developed (vs. a non-sequential algorithm), the fourth module utilizes an experiment where the computer sequentially estimates a single parameter in a linear discrete-time equation. This equation is derived from an energy balance describing heat transfer in a stirred tank. The theory follows the presentation of Young.¹⁸ This experiment demonstrates many of the convergence features of sequential estimators while including real-life features such as process and measurement noise as well as modeling errors. It is simple enough (one unknown parameter, first order o. d. e.) that the student can interpret the experimental and computational results. The discrete-time filter is then extended to continuous-time systems; the analogy to the LQP is pointed out. The experimental testing of state estimation by Hamilton et al.¹⁹ at the University of Alberta is a good applications paper for this section.

Due to a lack of time, the course does not cover topics such as Lyapunov functions (particularly as applied to suboptimal control and model reference adaptive control), non-interacting control, or multivariable frequency response design. (Continued on page 199.)

CHEMISTRY OF CATALYTIC PROCESSES

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MOST INDUSTRIAL REACTIONS are catalytic, and many process improvements result from discovery of better chemical routes, usually involving new catalysts. Because catalysis plays a central role in chemical engineering practice, it is strongly represented in chemical engineering teaching and research at Delaware. A graduate course entitled "Chemistry of Catalytic Processes" is designed to present a cross section of applied catalysis within the framework of detailed consideration of important industrial processes. The course brings together the subjects of chemical bonding, organic reaction mechanism, solid-state inorganic chemistry, chemical kinetics, and reactor design and analysis. There is no stronger evidence of the value of integrating chemistry and chemical engineering than the industrial successes in catalytic processing.

Five classes of industrial processes are considered in sequence: catalytic cracking, catalysis by transition metal complexes, reforming, partial oxidation of hydrocarbons, and hydrodesulfurization. Each class is introduced with a description of the processes, which is followed by details of the catalytic chemistry and process analysis and reactor design.

To the extent that each subject allows, ties are drawn between the reaction chemistry and process design. For example, the new zeolite cracking catalysts are used primarily because they have high selectivity for gasoline production, but they also have such high activity compared to the earlier generation of silica-alumina catalysts that they must be used diluted in a silica-alumina matrix to prevent overcracking. Their application has required redesign of catalytic crackers to accommodate rapid reaction predominantly in the riser tube (located upstream of what was formerly the fluidized-bed reactor); redesign must also accommodate a changed energy balance resulting

from the reduced coke formation on zeolite catalysts and must promote more complete coke removal in regeneration. The reactor design may be based on a simplified series-parallel reaction network, on the assumption of a small deviations from piston flow in the riser, and on a balance between the energy required for the endothermic cracking reactions and the energy produced in coke burn-off from catalyst particles in the regenerator.

There is no stronger evidence of the value of integrating chemistry and chemical engineering than the industrial success in catalytic processing.

The processes are introduced in an order leading roughly from the simplest to the most complex chemical concepts and from the best understood to the least well understood catalytic chemistry (Table 1). Cracking is the first subject presented because the zeolite catalysts have known crystalline structures and relatively well defined acid centers; the cracking reactions proceed via carbonium ion intermediates, giving well characterized product distributions. The second subject, catalysis by transition metal complexes, also involves well defined species and is unified by the idea of the cis-insertion mechanism, which is discussed on the basis of ligand field theory and exemplified in detail by Ziegler-Natta polymerization.

Reforming introduces metal catalysis, the concept of bifunctional reaction mechanism and ties with acid catalysis. Theory of metal catalysis is incomplete although solid-state theory and molecular orbital calculations on small metal clusters provide insight; a tie still remains to be drawn between catalysis by metal complexes and catalysis by clusters of metal atoms. The concluding topics of partial oxidation and hydrodesulfurization involve solid state and surface chemistry of transition metal oxide and sulfide catalysts; there is a thorough understanding of a few oxidation catalysts (for example, bismuth molybdate catalyzing ammoxidation of propylene) but for the most part the chemistry is not

well understood, and the ties between the chemistry and the process design cannot be well developed.

COHERENCE VIA CHEMICAL CONCEPTS

THE COHERENCE of the course is provided by the chemical rather than by the engineering concepts, and the latter are interwoven as dictated by their practical value to the various processes. For example, interphase mass transfer is considered in analysis and design of the gas-liquid reactors used in the oxo, Wacker, and vinyl acetate processes, which involve homogeneous catalysis by transition metal complexes. Mass transport in catalyst pores is important in hydrodesulfurization (affecting rates of the desired reactions and rates of reactions giving pore-blocking deposits); the unique phenomena of mass transport in the molecular-scale intracrystalline pores of zeolites are introduced with catalytic cracking and form the basis for an introduction to shape-selective catalysis. Analysis of reactor and catalyst particle stability is central to the discussion of catalytic oxidation processes, for which catalysts are selected and reactors designed to give high yields of valuable partial oxidation products and low yields of CO_2 .

Instrumental methods of analysis essential to catalyst characterization are introduced as they are appropriate to the process, giving a representation of the breadth of their usefulness. For example, chemisorption measurements, electron microscopy and x-ray line broadening to determine metal surface areas and crystallite sizes are introduced in discussion of catalytic reforming, which involves supported-metal bifunctional catalysts. Infrared spectroscopy is useful for probing the detailed structures of transition metal complexes (for example, the rhodium complexes used as oxo catalysts) and for indicating the structures of acidic centers on zeolite surfaces. Electron spin resonance and magnetization studies have provided essential information about oxidation and hydrodesulfurization catalysts containing transition metal ions.

The course is an attempted synthesis of chemistry and chemical engineering; the synthesis is traditional in practice, but not in teaching, and there is a lack of appropriate secondary literature sources. Consequently we have prepared a thorough set of typewritten notes (portions of which have been published as review articles

(1, 2)). The notes are based largely on primary literature, and since the literature of industrial processes does not give a good representation of current practice, the interpretations may sometimes be out-of-date and erroneous.

Many improvements in the course have resulted from criticisms given by practitioners, and we have attempted to include students from industry in classes with first-and-second-year graduate students. The course has been offered in the 4:30 to 6:00 P.M. time period, which is convenient to many potential students who are employed nearby. Response has been favorable enough that the course is also offered yearly as a one-week short course. Those attending have been predominantly industrial chemical engineers and chemists (in about equal numbers), some traveling from as far as the west coast and Europe. □

REFERENCES

1. Schuit, G. C. A., "Catalytic Oxidation over Inorganic Oxides as Catalysts," *Memoires de la Societe Royale des Sciences de Liege, Sixieme Serie, Tom I*, 227, 1971.
2. Schuit, G. C. A., and Gates, B. C., "Chemistry and Engineering of Catalytic Hydrodesulfurization," *AICHE Journal* 19, 417 (1973).

TABLE 1
Course Outline

- I. ZEOLITE-CATALYZED CRACKING AND RELATED PROCESSES
 - A. Processes
 1. Catalytic Cracking
 - a. Process Conditions
 - b. Reactor Operation
 - c. Regenerator Operation
 2. Hydrocracking and Isomerization
 - B. Reactions and Chemistry
 1. Chemical Bond Theory
 - a. Atomic Orbitals and Energy Levels
 - b. Molecular Orbitals
 - i. Linear Combinations of Atomic Orbitals
 - ii. Symmetry Aspects
 - iii. The Secular Determinant
 - c. Multiple Atom Systems
 - i. Hybridization Theory
 - ii. Electron-Deficient, Delocalized Molecular Bonds
 2. Carbonium Ions
 - a. Electron Deficiency Properties
 - b. Classical and Non-Classical Carbonium Ions
 - c. Reactivity and Characteristic Reactions
 3. Cracking Reactions
 - a. Thermal Cracking
 - b. Acid-Catalyzed Cracking
 - C. Catalysts
 1. Amorphous Catalysts
 - a. Preparation
 - b. Structure and Surface Chemistry
 - c. Acidity: Measurement and Correlation

George Schuit received his Ph.D. from Leiden and worked at the Royal Dutch Shell Laboratory in Amsterdam before becoming Professor of Inorganic Chemistry at the University of Technology, Eindhoven, The Netherlands. His research interests are primarily in solid state inorganic chemistry and catalysis, and his recent publications are concerned with hydrodesulfurization and selective oxidation of hydrocarbons. He has been on organizing committees for the Roermond Conferences and the Third International Congress on Catalysis, is a member of the Royal Dutch Academy of Sciences and is on the editorial board of the *Journal of Catalysis*. In 1972 he was National Lecturer of the Catalysis Society and Unidel Distinguished Visiting Professor at the University of Delaware; he now holds joint appointments at Eindhoven and Delaware.

Jon Olson obtained a Doctor of Engineering degree at Yale and worked for E. I. duPont de Nemours and Company before joining the faculty at Delaware. With wide ranging interests in

chemical engineering, he has recently done research concerning analysis of fixed-bed catalytic reactors, fouling of chromia/alumina catalysts, partial oxidation, and automotive emissions control.

Jim Katzer received a Ph.D. in Chemical Engineering from MIT and has been at Delaware since 1969. His primary research interests are catalytic chemistry and mass transport in catalysts. His recent work has emphasized applications of catalysis to pollution abatement, particularly catalytic reduction of nitrogen oxides, supported metal catalysis, catalyst poisoning mechanisms, and transport and reaction in zeolites.

Bruce Gates received his Ph.D. from the University of Washington. He did postdoctoral research with a Fulbright grant at the University of Munich and worked for Chevron Research Company before joining the Delaware faculty in 1969. His current research concerns hydrodesulfurization, catalysis by transition metal complexes and design and evaluation of synthetic polymer catalysts.

2. Crystalline (Zeolite) Catalysts
 - a. Structure and Surface Chemistry
 - i. Primary and Secondary Structural Units
 - ii. Type Y Zeolite
 - iii. Mordenite
 - b. Acidity
 - i. Chemical Probes
 - ii. Instrumental Probes
 - iii. Explanation from Structural Considerations
 - iv. Active Sites and Activity Correlations
- D. Reaction Mechanisms
 1. Reaction Chemistry Related to Surface Structure
 - a. Amorphous Catalysts
 - b. Zeolite Catalysts
 2. Hydrogen-Transfer Activity of Zeolites
 3. Activity and Selectivity Comparison of Zeolites and Amorphous Catalysts
 4. Reaction Network and Deactivation: Quantitative Models
- E. Influence of Catalytic Chemistry and Mass Transport on Choice of Processing Conditions
 1. Superactivity of Zeolites
 2. Mass Transport Effects in Zeolites; Shape-Selective Catalysis
 3. Effect of Zeolite Cracking Chemistry on Reactor and Regenerator Design
- F. Quantitative Reactor Design
 1. Riser-Tube Cracker Design
 2. Regenerator Design
- II. CATALYSIS BY TRANSITION METAL COMPLEXES
 - A. Processes
 1. Wacker Process
 - a. Reactions, Product Distribution, and Kinetics
 - b. Processing Conditions
 - c. Reactor Design
 2. Vinyl Acetate Synthesis
 3. Oxo Process (Hydroformylation)
 4. Methanol Carbonylation to Acetic Acid
 5. Ziegler-Natta Polymerization: Transition from Homogeneous to Heterogeneous Catalysis
 - B. Chemical Bond Theory
 1. Ligand Field Theory
 2. σ and π -Bonding in Complexes

- C. Catalysts
 1. Wacker—Pd Chloride
 2. Hydroformylation—Co and Rh Carbonyls
 3. Carbonylation—Rh-Phosphine Complexes
 4. Ziegler-Natta Polymerization—Transition Metal Chlorides and Metal Alkyls
- D. Reaction Mechanisms
 1. The General Cis-Insertion Mechanism
 - a. Experimental Evidence
 - b. Molecular Orbital Explanation
 2. Detailed Mechanisms of Particular Reactions
 - a. Ethylene Oxidation
 - b. Hydroformylation
 - c. Carbonylation
 - d. Stereospecific Polymerization
- E. Quantitative Process Design
 1. Design of Gas-Liquid Reactors; Mass Transfer Influence
 2. Preparation and Characterization of Solid Catalysts
 - a. Transition Metal Complexes Bound to Inorganic Surfaces
 - b. Complexes Bound to Organic Matrices
- III. CATALYTIC REFORMING
 - A. Process
 1. Principal Chemical Reactions
 2. Thermodynamics and Kinetics
 3. Supported Metal Catalysts
 4. Process Conditions and Reactor Design
 - B. Reactions and Chemistry
 1. Mechanisms of Metal Catalyzed Reactions
 - a. Hydrogenation-Dehydrogenation and H-D Exchange
 - b. Isomerization and Hydrogenolysis
 - c. Cyclization
 - d. Aromatization
 2. Chemical Bond Theory
 - a. σ - and π -Bonds
 - b. Delocalized Bonds
 - c. Bands in Metals
 - d. d-orbital Contribution to Transition Metal Bands
 3. Metal Catalysis
 - a. Electrons and Metal Bond Strength
 - b. Electrons and Adsorption on Metals

- c. Theoretical Calculations of Electronic Properties and Surface Bond Strength
 - d. Catalytic Activity: Surface Compound Correlations
 - e. Alloys
 - i. Miscibility Gaps and Surface Composition
 - ii. Catalytic Activity: Ligand and Geometric Effects
- C. Dual-Functional Supported-Metal Catalysts (Pt/Al₂O₃)
1. The Metal, Practical Considerations
 - a. Preparation and Characterization
 - b. Effects of Crystallite Size on Activity
 - c. Sintering and Poisoning
 - d. Alloys
 2. The Alumina Support
 - a. Preparation and Properties
 - b. Structure
 - c. Development and Control of Acidity
- D. Reaction Networks and Reaction Mechanisms
1. Dual-Functional Nature of Catalyst
 - a. Reaction Steps and Relation to Catalyst Functions
 - b. Studies with Physically Separated Functions, Mass Transport Considerations
 - c. Effect of Support Acidity on Reforming Reactions
 - d. Poisons and Poisoning Studies
 2. Cyclization Reaction Network and Reaction Mechanism
 3. Overall Network
- E. Relation of Processing to Catalytic Chemistry
1. Balancing the Strengths of the Catalyst Functions
 2. Mass Transport Effects on Selectivity
 3. Optimum Design of Dual-Functional Catalytic Systems
 4. Regeneration Procedures Related to Catalyst Structure and Stability
 5. Lumping in Fixed Bed Reactor Design for Many Reactions
- IV. SELECTIVE OXIDATION OF HYDROCARBONS CATALYZED BY METAL OXIDES
- A. Processes
1. Phthalic Anhydride
 - a. Reactions
 - b. Process Conditions
 2. Maleic Anhydride
 3. Acrolein and Acrylonitrile
 4. Ethylene Oxide
- B. Reactions and Chemistry
1. Chemical Bond Theory
 - a. Electrostatic Bonds in Solid Oxides
 - b. Changes in Cation Oxidation State
 2. Allylic Intermediates
 3. Mars-van Krevelen Mechanism
 4. Reaction Network for Naphthalene Oxidation
- C. Catalysts
1. Composition and Structure
 - a. V₂O₅ and MoO₃-V₂O₅
 - b. Bi₂O₃-MoO₃
 - c. Fe₂O₃-MoO₃
 - d. UO₃-Sb₂O₃
 - e. Cu₂O
 2. Oxidation Selectivity
 - a. Correlations
 - i. Oxygen Bond Strength
 - ii. Metal Oxide Structure
 - b. Oxygen Interchange with Metal Oxides
 - c. Microscopic Considerations, Active Sites
- D. Detailed Reaction Mechanisms involving Olefins—Examples Based on Solid and Intermediate Complex Structures
1. Solid Structures, Bismuth Molybdate and Uranium Antimony
 2. Surface Chemistry
 3. Reactant-Surface Interactions
 4. Reaction Mechanism
- E. Quantitative Reactor Design—The Hot Spot Problem
1. Influence of Catalytic Chemistry on Choice of Processing Conditions; the Need for Selective Catalysts
 2. Fluidized Bed Reactors
 3. Fixed Bed Reactors
 4. Heat and Mass Transfer in Catalyst Particles
 5. Catalyst Particle Stability
- V. HYDRODESULFURIZATION
- A. Processes
1. Sulfur-containing compounds in Petroleum and Coal-Derived Liquids with Hydrogen
 2. Compositions of Co/Mo and Ni/Mo Catalysts
 3. Processing Conditions
 - a. Petroleum Distillates
 - b. Petroleum Residua
 - c. Coal
 4. Reactor Design: Fixed and Fluidized Beds
- B. Reactions and Chemistry
1. Model Reactant Compounds
 - a. Desulfurization Reaction Networks of Thiophene and Benzothiophenes
 - b. Kinetics of Hydrodesulfurization of Thiophene and Benzothiophenes
 2. Petroleum Feed Stocks
 - a. Composition of Feed Stocks
 - b. Simplified kinetics for Petroleum Feed Stocks
- C. Catalysts
1. Structure of Cobalt Molybdate and Nickel Molybdate Catalysts
 2. Texture
 3. Interaction of Catalyst with the Support
 4. Effects of Promoters
 5. Catalytic Sites
 - a. Monolayer Model
 - b. Intercalation Model
- D. Reaction Mechanisms of Model Compounds
- E. Process Design
1. Relation of Process Design to Catalytic Chemistry of Hydrodesulfurization and Side Reactions
 2. Influence of Intraparticle Mass Transport on Catalyst Effectiveness
 3. Catalyst Aging: Pore Blocking and Interstitial Deposition
 4. Hot Spots and Reactor Stability; Analysis of Trickle Bed and Slurry Bed Reactors

MULTI-PURPOSE VIDEO-TAPED COURSE IN DATA ANALYSIS

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The iterative process of formulating a mathematical model, design of experiments to test that model, analysis of the data from these experiments, the use of the experimental results to modify the hypothesized model, and the incorporation of the model in larger systems is one which is fundamental to all branches of engineering. Although this process is basic to the engineering analysis of problems and design procedures, there exist few courses in which the complete cycle is treated. The difficulty with teaching the complete loop by usual methods is that typically the background of the students is relatively disparate, therefore one is seldom able to teach to a body of students with uniform backgrounds. Nonetheless, we feel that such a course is important to engineering graduates so we have attempted to approach the problem using video tape.

A significant advantage in treating this type of subject, where backgrounds may not all be the same, is offered by video-tape and video-tape cassette capabilities. These tools permit different students to use different portions of the same course, and also permit these students to progress at varying rates as they so desire. We attempted to design a course which, for educational efficiency, we tried to fit to the needs of both continuing education students and full-time students on the campus, and, in addition, created the course in modular form so that it could be taught as various series of self-contained mini-courses to students who wanted only a portion of the overall material.

The course is multi-purpose basically in two different ways. One, there is a combination of sub-units which can be selected to accomplish the educational objective of each student, and two, the course applies to a variety of educational situations. The variety of path choices was accomplished by designing the course as a series of self-contained mini-courses which can be assembled to

One is, in effect competing with a program like Sesame Street (with a 6 million dollar budget) in production and entertainment value while trying to present a much more sophisticated level of concepts to a much more critical and discriminating audience.

form a maxi-course in a variety of ways, depending on the education background of the particular student and his particular educational objective. The variety of educational situations which the course can be applied are: a) normal or self-paced classroom use, b) continuing education use, c) broadcast TV to larger segments of the community. An important but not primary purpose of this course is also to furnish a pilot effort toward a video correspondence Master's degree program which would permit a student at a remote location to complete requirements for a Master's degree by selection of an appropriate series of video courses. The course consists of 43 thirty-minute video tapes which are as shown in Table I.

Table 1—Course Content

Unit		Parts
1	Introduction	1
2	Curve Fitting	4
2-4	Nomography	
3	Statistical and Numerical Errors	3
4	Differences and Lagrangian Methods	3
5	Least Squares	3
6	Population Characteristics	2
7	Probability	2
8	Sample Characteristics	3
9	Analysis of Variance	3
10	Regression	3
11	Matrix Regression	3
12	Dimensional Analysis	2
13	Model Building	2
14	Time Series	2
15	Inference	2
16	Factorial Designs	3
17	Systems/Networks	2

COURSE CONTENT

THE COURSE IS ORGANIZED in 17 units.

Each of these units has from two to four parts with the exception of Unit 1 which is a single part introduction. Each part represents a 30-minute lecture. At Purdue the remaining part of a 50-minute period is used for discussion. In each of the units about half of the material presented is actual examples taken from practice.

UNIT 1 is the introduction and it sets the objective for the course, which is to interface theory and data. The use for the interface is to build models, plan experiments, process data, interpret data, and design data systems.

UNIT 2 is concerned with curve fitting and nomography, to permit summarizing data so that it can be interpolated and extrapolated, to check theory, and for empirical prediction of new data. The two parts to the curve fitting problem are: First, to determine the form of curve. This is usually accomplished by plotting the data in various ways until a straight line results. Second, to determine the parameters by fitting a straight line to the rectified data using the method of selected points, method of least squares. One of the parts of this unit discusses nomography, a graphical representation of the functional relationship among variables. We give a brief introduction to methods of constructing nomographs emphasizing addition, subtraction, multiplication and division.

UNIT 3 is concerned with statistical and numerical errors. The object here is to identify and separate statistical error, those random errors that are associated with measurement; and systematic error, those that are not random errors; and further errors that result from operation on the data numerically. We end the unit with a discussion of the meaning of accuracy and precision both in the statistical sense and in the sense of relating these concepts directly to the numbers involved in experiments.

UNIT 4 treats differences and Lagrangian methods. One often has to interpolate between data points, especially when data is in tabular form, and it is also often necessary either to differentiate or integrate tabulated data. We discuss the divided differences, backward, forward and central finite differences. We end with a discussion of Lagrangian methods specifically applied to numerical differentiation and numerical integration.

In UNIT 5 the principle of least squares is considered in detail. Also we begin an early discussion of how least squares and linear regression are related, since we use linear regression to predict statistical behavior. The principle of least squares is usually used to fit the data in regression analysis. We give a discussion of the use of least squares to identify important variables and consider the more complex polynomial least squares and nonlinear least squares.

In UNIT 6 population characteristics are discussed so that we can use statistical models of the various distribution functions to describe sample spaces. We discuss some of the simple distributions—the uniform distribution, the normal distribution—and the meaning of these distributions in a probability sense.

UNIT 7 is more detailed discussion of probability and investigates the meaning of experiments, outcomes, sample spaces and elements of sample spaces, and how these

Robert Greenkorn, after five years as a naval aviator, returned to Wisconsin to obtain B.S., M.S., and Ph.D. in Chemical Engineering from the University of Wisconsin, 1954, 1955, and 1957 respectively. He spent the academic year 1957-58 at the Norwegian Technical Institute in Norway as a post-doctoral fellow. From 1958 to 1963 he was research engineer with Jersey Production Company in Tulsa and lecturer in evening division of University of Tulsa. From 1963 to 1965 was Associate Professor of theoretical and applied mechanics at Marquette University. Associate Professor in the School of Chemical Engineering at Purdue University from 1965 to 1967. Professor and Head of the School of Chemical Engineering 1967-1973; Acting Head of Aeronautical and Astronautical Engineering, June 1973-Aug. 1973. Asst. Dean for Research, Director, Institute for Interdisciplinary Engineering Studies, and Associate Director of the Engineering Exp. Station, Aug. 31, 1972-present. (LEFT)

David Kessler has taught at Purdue University since 1964. Prior to his academic career, he was employed in process engineering and statistical quality control by the Dow Chemical Company and in process and product development by the Proctor and Gamble Company. He did his undergraduate work at Purdue and received his graduate degrees from the University of Michigan. His current research interests are flow in heterogeneous, non-uniform and anisotropic porous media, momentum transfer in multiphase flow, and bioengineering (artificial blood, cardiac contractility, and hemorrhagic shock). He is co-author with Professor Greenkorn of the undergraduate text "Transfer Operations" (McGraw-Hill, 1972). (RIGHT)



various concepts are utilized in probability formulations. A short discussion of probability in terms of logic and Venn diagrams is included. Marginal and conditional probabilities and the Bayes theorem are also discussed.

In UNIT 8 we discuss sample characteristics, concentrating on utilizing the normal distribution from a designed experiment, look at the probability meaning of distribution functions in terms of the normalization of these distribution functions and the relationship to probability. We discuss the use of various kinds of tabulated probability distribution functions and the distribution of sample characteristics. The unit ends with a discussion of confidence intervals and a preliminary treatment of hypothesis testing and type I and type II errors. These last topics are repeated in more depth in Unit 15.

In UNIT 9 we begin our discussion of experimental design by introducing the analysis of variance technique—dissecting total variation in such a way that various kinds of experimental effects are eliminated. The analysis of variance allows us to show how experiments may be de-



Professors Greenkorn (left) and Kessler (right) on the set for filming a unit of their multi-purpose video tape.

signed so that we can get the most information from the data. We discuss the one-way classification and two-way classification (and randomized complete block designs). The linear models associated with these kinds of designs are discussed as are the short-cut methods of calculating the analysis of variance table.

REGRESSION IS DISCUSSED in UNIT 10 based on the units on least squares and analysis of variance. Analysis of variance is used to interpret the meaning of regression coefficients in the various kinds of regression models. The "extra sum of squares" principle is introduced and methods for analyzing the meaning of the various regression coefficients in models that have more than one independent variable are considered.

In UNIT 11 regression analysis is viewed from the standpoint of matrix manipulations. There is a short review of linear algebra and matrix theory and then the matrix approach to regression is discussed with use of the Doolittle method for determining regression coefficients.

In UNIT 12 we enter a discussion of dimensional analysis, a systematic way in which the number of variables required to describe a given experimental situation is reduced, since normal model building uses dimensionless forms. We also investigate the relationship between dimensional analysis and the differential equations which are the models for various experiments.

Model building is considered in UNIT 13 in a philosophical sense and we try to answer the questions: What is a model? How does it relate to the real world? How do we build models? Mathematical and physical analogs are discussed. Example models are formulated through use of an entity balance.

In UNIT 14 we treat time-dependent stochastic processes, that is, processes where the parameters of the probability density and distribution functions are time-dependent. Much of what we do in engineering is time-dependent and we cannot ignore this time-dependence. Ways and means of investigating the statistical properties of systems that do depend on time are considered. The ergodic assumption is also discussed.

THE PROBLEM OF INFERENCE and the estimating of population parameters from experiments in a detailed manner is discussed in UNIT 15. The meaning of inference is investigated in terms of the various kinds of distribution functions. The meaning of hypothesis testing and multiple-hypothesis testing are discussed and the operating characteristic curve for various kinds of hypothesis tests is introduced.

In UNIT 16 we consider factorials which are posed as experimental designs—randomized block and Latin square. The meaning of factors in experiments is analyzed using the linear hypothesis and is based on the discussion of inference and hypothesis testing in the previous unit. We consider multi-factor experiments and how one confounds data in a factorial experiment. The use of aliases in designing fractional factorial experiments is also discussed.

In UNIT 17 we look at the total data acquisition and analysis system. Network models and graph theory are discussed. Information flow as related to executive programming is also considered.

USE OF COURSE

WE PRESENTLY TEACH the course in its entirety over the Purdue closed-circuit video facilities. As can be seen from the network diagram, a number of ways to trace out either the total course or selected sub-sets are available. Typical mini-courses might be Units 9, 10, and 11 in Regression or Units 9 and 16 in Experimental Design. Most of the individual Units also stand alone without reference to other units.

In the future we hope to incorporate all segments of this course on video cassettes which can be played over monitors equipped so that the tape may be stopped without erasing the picture from the screen. This will permit much greater economy in presenting graphical material, in that the student can simply stop the monitor and hold the picture on the screen rather than wasting several minutes of tape for a static display.

DIFFERENCES FROM CONVENTIONAL COURSES

IT IS INTERESTING to observe the reactions of students when viewing a course on what looks like a conventional television set. They react to the course much as one observes groups of people reacting to television programming in

In the future we hope to incorporate all segments of the course in video cassettes which can be played over monitors equipped so that the tape may be stopped without erasing the picture.

their home—that is, there is far less reluctance to create a disturbance, much as one will carry on a conversation in one's own living room while the TV set is on. There also is a much greater need for entertainment value to hold the student's attention than in an ordinary class room lecture, because the students, seeing the material on the television set, expect a far more professional degree of treatment than is true in the ordinary lecture. One is, in effect, competing with a program like Sesame Street (with a six million dollar

one of the strongest reasons why television tapes must be entertaining—the student cannot participate by talking back to a television screen in the same way that a good lecturer can stop and ask questions at a pertinent point in the presentation, and listen to feedback from students. At present there is no practical possibility of branching or changing pace in a television presentation as there is in the ordinary classroom lecture. We hope to circumvent this difficulty to some extent by keeping individual presentations short and thus permitting the student to select among a variety of short presentations so that if the pace becomes too slow or too fast he can alter the pace to suit himself. In the future we also hope to tape a greater variety of example problems so that the student can go directly to an example problem if he has difficulty with the theoretical concept which has been presented on the tape.

In taping the course we used a producer/director and three cameramen, with visual material on rear-projection slides and newsprint. The set is shown in the photo. One of the major difficulties is the preparation of visual material (about 1000 items for this course). We hope to do some work soon on automating much of this with the computer. Our current production costs (exclusive of authors) is about \$300 per Unit. □

TO DEPARTMENT CHAIRMEN:

The staff of CHEMICAL ENGINEERING EDUCATION wishes to thank the 72 departments whose advertisements appear in this sixth graduate issue. We also appreciate the excellent response you gave to our request for names of prospective authors. We regret that, because of space limitations, we were not able to include some outstanding papers and that certain areas are not represented. In part our selection of papers was based on a desire to complement this issue with those of the previous years. As indicated in our letter we are sending automatically to each department for distribution to seniors interested in graduate school at least sufficient free copies of this issue for 20% of the number of bachelor's degrees reported in "ChE Faculties." Because there was a large response to our offer in that letter to supply copies above this basic allocation, we were not able to fully honor all such requests. However, if you have definite need for more copies than you received, we may be able to furnish these if you write us. We also still have some copies of previous Fall issues available.

We would like to thank the departments not only for their support of CEE through advertising, but also through bulk subscriptions. We hope that you will be able to continue or increase your support next year.

Ray Fahien Editor

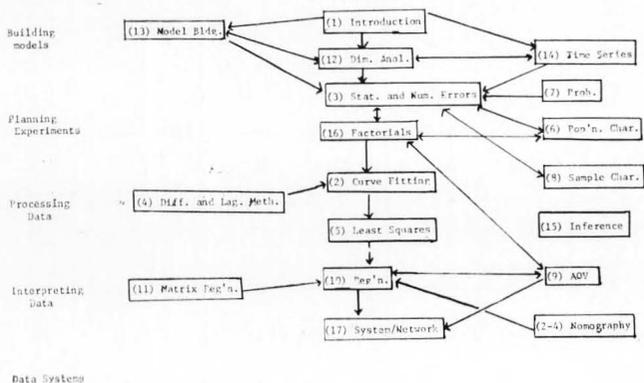


FIGURE 1. Network Diagram

budget) in production and entertainment value, while at the same time attempting to present a much more sophisticated level of concepts to a much more critical and discriminating audience.

It is also interesting that the students do not perceive the pace at which the course is going. At times they feel that the material is coming quite slowly when, in fact, because of the compactness of the presentation, material is being presented at a far greater rate than was ever possible in an ordinary classroom lecture. Students are also far more critical of mistakes that appear on a television tape than mistakes that appear in an ordinary classroom lecture. (The preparers of the tape, of course, should also be extremely critical of such mistakes because these mistakes will be perpetuated from year to year.)

It is interesting that the television tape prompts a far greater need on the student's part to be supplied with All the material than does an ordinary classroom lecture—students appear to feel that since a course is taught on TV there should be no need to consult outside references. Again, this seems to be a psychological set induced by commercial TV viewing. In the future we may attempt to remedy this by calling for more response from the class during the television taping via short questions, etc. This, perhaps, is

ADVANCED THERMODYNAMICS

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THE COURSE TO BE discussed here is Engineering 510 "Advanced Thermodynamics," which is a "core" course in the College of Engineering at Notre Dame. The only prerequisite is one semester of undergraduate thermodynamics, so that engineering graduate students of all disciplines can qualify for the course. The course is required for graduate chemical engineers and is often taken as an elective by engineers of other disciplines. The latter group of students generally

The challenge is to substantially enlighten and expand the knowledge of the chemical engineers . . . and provide a strong fundamental unit of thermodynamics for the non-chemical engineers who may compose as much as half of the class.

has a one-semester background from, say, Holman¹ or Reynolds and Perkins,² while the chemical engineers are more thoroughly schooled in undergraduate thermodynamics, usually having two semesters of formal study, covering both physical and chemical thermodynamics, as well as additional exposure in "material and energy balances" and in physical chemistry.

The challenge is to present a course that will substantially enlighten and expand the knowledge of the chemical engineers, while at the same time will provide a strong, fundamental unit of thermodynamics for the non-chemical engineers, who may compose as much as one-half of the class. That thermodynamics, a discipline based on a few fundamental laws and their application, is taught at the graduate level to chemical engineers is probably an honest reflection of the fact that chemical engineers, despite their background, accept their bachelor's degree with a foundation in

thermodynamics that can be shaken without excessive effort.

The discussion that follows maps out the material covered in the course in its chronological appearance. The objective is to stress the aspects of the course that are given the most emphasis during the semester as well as to give a sense of the continuity of the topics treated. The several sections that follow form a rough syllabus of the course, covering approximately 14 weeks, or 42 meetings.

1. Review of Concepts (2 weeks)

Before starting a formal presentation of thermodynamics in a "postulational" manner, a review of the traditional "inductive" thermodynamics is performed. To make this review attractive, it is presented in a historical context, much in the spirit of Tisza,³ starting with Galileo and Torricelli, presenting the caloric theory and its shortcomings, continuing with the contributions of Carnot, Kelvin, Mayer, Joule, and finishing with the resolution of thermodynamics into its laws which occurred in the middle of the nineteenth century. Besides providing a review of this "thermodynamics of cycles," these initial lectures are designed to show the student that the difficulties that were encountered in the development of thermodynamics, historically speaking, are the same difficulties that trouble the contemporary student of thermodynamics. Besides treating the laws of thermodynamics and their function, lectures are presented on the concepts of reversibility and irreversibility, and the temperature concept and its measurement.

2. The Postulational Development of Thermodynamics (5 weeks)

The only text required for this course is Callen.⁴ Lectures structured about the first seven chapters of Callen are employed with the following philosophy: Take away the "laws" of thermodynamics from the student and develop a self-con-



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sistent, self-contained mathematically structured discipline which can be shown to provide the user with analytical tools equivalent to the "laws." One drawback to inductive thermodynamics is that the laws evolving from it are based on experimental observation (specifically, "thought" experiments), and the tendency of students is to develop "rules-of-thumb" which are not completely general. Consequently, the use of these rules-of-thumb can often lead to difficulties, much in the way paradoxes, or apparent contradictions, arose in the historical development of thermodynamics. A primary function of this development is to demonstrate that postulational thermodynamics is applicable to any thermodynamic problem, including those from which inductive thermodynamics evolved. Key points of emphasis in this section are:

- The informational content of thermodynamic fundamental relationships and the equations of state that come from them. The roles of the Euler and Gibbs-Duhem equations in providing the link between equations of state and fundamental relationships are detailed. The fact that one observes an incomplete set of equations of state in the laboratory is used to demonstrate the need for a basis, or reference, for the family of thermodynamic energy functions (internal energy, enthalpy, etc.).
- The equivalence of the extremum principles for entropy and internal energy and their extension by Legendre transformation to non-isolated systems. The Gibbs minimum principle for systems at some given (P_o, T_o) is used later as the starting point for handling complex chemical systems. (See Section 3.)

- The Jacobian transformations in concert with the Maxwell relations, presented as a system for handling the expression of process derivatives in terms of measurable quantities such as specific heat at constant pressure C_p , isothermal compressibility κ_T , and the coefficient of thermal expansion α , i. e., the three independent derivatives of the P-T basis.

The utility of the third point above can be accentuated by having the student demonstrate his capability at developing an H-S diagram for some substance, or at least the necessary formalism to do so. Generating formulae for isobars and isotherms in H-S space is fairly straightforward, but deriving a formula for the coexistence curve of, say, the saturated vapor is a bit more opposing (Denbigh⁵ has a related problem in which an expression for the specific heat at coexistence for a phase is desired.):

$$\left(\frac{\partial h}{\partial s}\right)_{\text{sat. vap.}} = \text{slope of saturated vapor locus in H-S space}$$

$$dh = \left(\frac{\partial h}{\partial T}\right)_P dT + \left(\frac{\partial h}{\partial P}\right)_T dP \quad (2-1)$$

$$ds = \left(\frac{\partial s}{\partial T}\right)_P dT + \left(\frac{\partial s}{\partial P}\right)_T dP \quad (2-2)$$

Along the coexistence curve, the Clausius-Clapeyron equation states

$$dP = \left(\frac{\Delta h}{T\Delta v}\right) dT \quad (2-3)$$

and so

$$\left(\frac{\partial h}{\partial s}\right)_{\text{sat. vap.}} = \frac{TC_p + v(1-T\alpha)(\Delta h/\Delta v)}{C_p - v\alpha(\Delta h/\Delta v)} \quad (2-4)$$

since

$$\left(\frac{\partial h}{\partial T}\right)_P = C_p, \quad \left(\frac{\partial h}{\partial P}\right)_T = v(1-T\alpha), \quad \left(\frac{\partial s}{\partial T}\right)_P = C_p/T, \quad \left(\frac{\partial s}{\partial P}\right)_T = -v\alpha,$$

and where C_p , α , v are evaluated for the saturated vapor phase, and Δh and Δv are the enthalpy and volume changes upon vaporization respectively.

One drawback to inductive thermodynamics is that laws evolving from it are based on experimental observation and students tend to develop "rules of thumb" which are not completely general.

Mastery of thermodynamic manipulations for pure substances, such as Jacobian transformations and Maxwell relations, is essential to developing confidently the complex expressions that are required, e.g., to describe mixtures (See Sec-

tion 6) while a firm basis of the thermodynamic extremum principles is necessary to realize the stability criteria for pure and multicomponent systems (See Section 5).

3. The Application of the Gibbs Minimum Principle to Complex Chemical Equilibria (2 weeks).

Zeleznik and Gordon⁶ have applied the Gibbs minimum principle to a general system of p phases and m species at some fixed (P_0, T_0) , and it is my experience that incorporation of their derivation into the course provides a quick, powerful method for the student to set up a complex chemical equilibria problem in a form amenable to computer solution. The derivation is lengthy and only the results will be presented here with accompanying comments.

That thermo is taught at the graduate level to ChE's is probably a reflection of the fact that they accept their B.S. degree with a foundation in thermo that can be shaken without excessive effort.

For the reacting system above, one solves the following set of equations:

$$\sum_i \sum_{\alpha} a_{ij} N_i^{\alpha} - b_j^0 = 0 \quad j = 1, \dots, l \quad \text{for elements} \quad (3-1)$$

$$\sum_i \sum_{\alpha} A_{ir} \mu_i^{\alpha} = 0 \quad r = 1, \dots, mp-l \quad \text{for } mp-l \text{ independent reactions} \quad (3-2)$$

where a_{ji} is a chemical subscript for element j in species i , α is the phase superscript, N_i is moles of species i , b_j^0 is the total number of gram-atoms of element j in the system, and A_{ir} is a stoichiometric coefficient for reaction r . The problem thus becomes mp equations in mp unknowns, namely, the set $\{N_i^{\alpha}\}$ $i = 1, \dots, m; \alpha = 1, \dots, p$. Each member of Equation (3-2) is called a reaction affinity.

If the reaction mechanism is unknown (or unspecified) the problem enlarges somewhat as Equation (3-2) is replaced by

$$\mu_i^{\alpha} + \sum_j \lambda_j a_{ij} = 0 \quad \text{for } i = 1, \dots, m; \alpha = 1, \dots, p \quad (3-3)$$

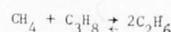
The problem is now $(mp+l)$ equations in $(mp+l)$ unknowns, namely $\{N_i^{\alpha}\}$ as before, and $[\lambda_j]$, $j = 1, \dots, l$, which are a set of Lagrangian multipliers introduced in applying the Gibbs minimum principle.

An important point brought out by this approach is the equivalence of problems, with and without a reaction mechanism, as the final equi-

librium state does not depend on the choice of a particular mechanism but rather on the choice of permissible species in the system. Elimination of $[\lambda_j]$ from Equation (3-3) will yield Equation (3-2), i. e., a possible set of reactions.

There are several difficulties inherent in adopting the Zeleznik-Gordon treatment directly for instructional purposes:

- Charge must be treated as an "extra" element, to be electroneutralized rather than conserved. Furthermore, free electrons are a species as well as a charge. The definition of species becomes "any entity for which the concentration at equilibrium is desired."
- In phase equilibria problems, where there are no reactions, conservation of elements, Equation (3-1), can either provide too many or too few constraints. One must replace Equation (3-1) with a set of equations conserving species rather than elements. If one has a problem in which only some of the species are reacting and some are not, and they have common elements, the statement of the problem becomes even more complicated. It is not satisfactory to consider all reactions permissible by stoichiometry as some will have rates so slow as to be disregarded. For example, in the phase equilibria of a natural gas system containing CH_4 , C_2H_6 , and C_3H_8 , it is of no interest to consider the possible reaction:



In other words, good judgment must be exercised in applying the Zeleznik-Gordon scheme.

- A traditional way of describing a m -component vapor-liquid phase equilibria problem is (See p. 47 of Reference 9, e.g.):
 $m + 2$ equations:

$$\mu_i^g = \mu_i^l \quad i = 1, \dots, m$$

$$P^g = P^g(v^g, T, \{y_i\})$$

$$P^l = P^l(v^l, T, \{x_i\})$$

$m + 2$ unknowns:

$$(T, v^g, v^l, y_1, y_2, \dots, y_{m-1})$$

The demonstration of the equivalence of this problem to that of Zeleznik and Gordon is made intricate by the fact that the Zeleznik-Gordon scheme, by virtue of solving for $\{N_i^{\alpha}\}$, suggests a batch process with finite phases, while the above problem makes no specification of phase size. The comparison of the two descriptions is presented in the course.

4. The Phase Rule (1 week).

The phase rule, written as

$$F = C - P + 2 \quad (4-1)$$

or

$$F = C - P + 2 - R, \quad (4-2)$$

where R is restrictions is one of these rules-of-thumb that most students feel they understand

by the time they reach the graduate level. Because this is often not the case, I generally start with an example complicated enough to produce a myriad of answers for the degrees of freedom f , and then backtrack, beginning at the beginning. Rather than deriving the rule as given above, I state the phase rule as:

“the number of degrees of freedom in the intensive phase variables = the number of independent intensive phase variables—the number of restrictions”

For example, consider the 3-component, 3-phase system (solid-liquid-vapor) where the components will be specified as A, B, C. The independent intensive variables are 12 in number

$$T^S, P^S, x_A^S, T_B^L, P^L, x_A^L, x_B^L, T^G, P^G, x_A^G, x_B^G$$

and the restrictions are 10:

$$T^S = T^L = T^G$$

$$P^S = P^L = P^G$$

$$\mu_i^S = \mu_i^L = \mu_i^G, \quad i = A, B, C$$

Thus $f = 2$, as can be readily obtained from Equation (4-1). The difficulty arises interpreting R in Equation (4-2). Consider the restrictions:

$$1) P = P_0$$

and

$$2) x_B^G = x_C^G = 0$$

In the first, logic dictates that f reduce to 1, and the form of analysis suggested introduces

$$P^S = P^L = P^G = P_0$$

or

$$f = 12 - 11 = 1$$

The restrictions (2) above do not affect f as there occurs a “balance”:

x_A^G, x_B^G are removed from the independent intensive variables and $\mu_A^G = \mu_A^L$ and $\mu_B^G = \mu_B^L$ can be removed from the restrictions. Thus the problem is

$$f = 10 - 9 = 1$$

Experience has shown that this detailed approach increases the student's confidence.

Since the phase rule makes no specification concerning the size of the phases (indeed, they could be considered infinite), the effect of “Batching” or, in a flow process, the setting of flow rates to a vessel can require careful examination. For example, consider the single (liquid) phase esterification reaction of ethyl alcohol and acetic acid at fixed T_0, P_0 . If one applies the phase rule Equation (4-2) directly

$$f = 4 - 1 + 2 - R$$

where $R = 3$: $P = P_0$, $T = T_0$, and 1 reaction ($mp-l = 1$), or $f = 2$. But one recognizes that if one batches the system identically each time,

i. e., fixes $[N_i] = [N_{i0}]$, one gets the same equilibrium composition in the vessel. Thus, the batching constitutes 2 restrictions. It can be seen by noticing that

$$x_i = \frac{N_{i0} - \Delta N_i}{\sum_i N_i}$$

for reactants and

$$x_i = \frac{N_{i0} + \Delta N_i}{\sum_i N_i}$$

where, in this particular case, EQUATION, as moles are conserved. Thus, e. g.,

$$x_i = a_i - z \quad (\text{reactants})$$

$$x_i = a_i + z \quad (\text{products})$$

and the single variable z replaces the 3 independent variables of the set $[x_i]$ ($\sum x_i = 1$), and batching in this case constitutes 2 restrictions.

Furthermore, the quantity ($mp-l$) used to denote reactions in the Zeleznik-Gordon scheme is really more general than that. One should consider it as representing the number of independent affinities, including those which describe a phase transformation:

$$\mu_i^\alpha - \mu_i^\beta = 0 \quad \text{for species } i \text{ and phases } \alpha \text{ and } \beta$$

Care must be taken not to count such a transformation twice, once as a reaction (transformation) in the set ($mp-l$) and once as a chemical equilibrium. For example, consider a vapor-liquid equilibrium between $\text{CH}_4, \text{C}_2\text{H}_6, \text{C}_3\text{H}_8, \text{CO}_2$, typical of a natural gas mixture prototype. For this system, $mp-l = 8-3 = 5$, yet common sense suggests 4 phase equilibria. The fifth “reaction” is the one cited in (2) of Section 3. The point here is not only should that reaction possibility be discarded but also that $mp-l$ includes that 4 chemical equilibria, i. e., phase transformations.

Applications relating to how many variables in a real process must be specified to produce a unique experiment (i. e., reproducible) can assume many forms and can be both interesting and challenging.

5. Stability Phenomena (2 weeks).

A brief introduction to phase stability (thermal and mechanical) and diffusional stability is presented. Phase stability is discussed in many texts, e. g., Callen,⁴ and can be demonstrated easily with the van der Waals equation. Some mention is made in passing of the fact that the

(Continued on page 198.)

WASTEWATER ENGINEERING FOR CHEMICAL ENGINEERS

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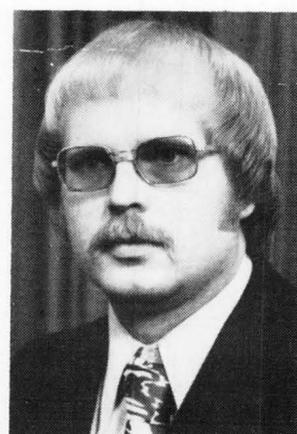
IN THE PAST FIVE YEARS, the areas of research and development interest for chemical engineers have expanded to include environmental topics. To see this, one has only to look at advertisements for industrial positions in our trade journals or at the listings of active research areas in graduate programs in the fall issue of this journal. Yet, coverage of wastewater topics in most chemical engineering programs is limited to a few specific examples introduced by instructors with experience in the field.

This paper describes "Wastewater Engineering," a graduate course oriented for the specific needs and backgrounds of chemical engineers. It evolved under the somewhat unusual circumstances that in the 1965-1970 period there were no active teaching or research programs in Environmental Engineering (or, as it was known then, Sanitary Engineering) at Case Western Reserve University. This vacant niche in the ecology of the School of Engineering has been occupied by a Graduate Chemical Engineering Wastewater Program built around the subject course and a complementary program on Water Resources in the Systems Engineering Department. Further development of "Wastewater Engineering" was fostered by hiring of faculty with specific background in the field and by a training grant (jointly administered between Chemical Engineering and Systems Engineering) from the U. S. Environmental Protection Agency, Office of Manpower and Training.

The graduate chemical engineering course on wastewater originated in response to a wide appeal for environmentally oriented courses. Many others enrolled besides chemical engineering graduate students, including undergraduates (mainly chemical engineers), graduate students in other fields and part-time students already employed in industry. The initial offerings in 1969

and 1970 were as a seminar or special-topics course. This was followed in 1971 by a structured course devoted principally to wastewater analyses and treatment technology. That course also dealt with water quality criteria and air pollution topics, hence its title "Environmental Quality: Measurement and Improvement." At the time, it was the only substantial environmental course, graduate or undergraduate, available in the engineering school.

"Wastewater Engineering," the present graduate course, was first taught in 1973. Now, an undergraduate course on wastewater or an introductory Sanitary Engineering course is a prerequisite. We assume that the students are familiar with water quality criteria, units of



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measurement, wastewater analyses and the common schemes for municipal wastewater treatment.

The discussion here covers both the lecture topics and associated laboratory experiments. Because adequate references have been provided, we only list the lecture topics and discuss the reasons for their selection. In the lectures, Chemical Engineering methods applied to wastewater technology take away some of the mystique. Still, empirical methods play a large part in characterizing wastewaters and their treatment. Hence, the laboratory is an important complement to the lectures. Since no published laboratory manual is available, we have consolidated our experience over the last few years by providing details on the objectives and suggestions for carrying out the experiments. Finally, we touch briefly on the relationship of "Wastewater Engineering" to other courses in our program.

COURSE CONTENT

TABLE 1 LISTS THE SPECIFIC topics covered. Each topic is presented starting with fundamental considerations and proceeding to rational methods for design specification or process analysis. Comprehensive problems are assigned, based on actual wastewater treatment experience whenever possible. Table 1 includes recommended texts. Locating suitable books was a problem, since environmental engineering texts generally devote considerable coverage to fundamental physical chemistry, transport phenomena and reaction kinetics.

"Wastewater Engineering," as a course for specialists in the field, concentrates on the widely used minimum-operating-cost "workhorse" processes, which can remove many pollutants together. Biological treatment heads the list of these topics, as the unit process of choice for removal of biodegradable organic pollutants from municipal or industrial wastewaters. It is difficult to conceive of other treatments which could be economically competitive to biological treatment. Sedimentation also is stressed, as an integral part of biological waste treatment processes and, in its own right, as the unit operation of choice for removal of settleable pollutants. Precipitation is widely used in municipal and industrial wastewater treatment for removal of inorganic pollutants by conversion to insoluble forms and sedimentation or other liquid-solid separations. Oxidation-reduction processes are used principally in in-

TABLE 1
Topics In Wastewater Engineering

Topics	Textbooks
1. Biological Waste Treatment (15 lectures)	Busch ¹
a. Basic microbiology.	
b. Stoichiometric and kinetic relations of mixed cultures, including both organic and inorganic substrates.	Weber, ² Ch. 11
c. Biodegradability and respirometric measurements.	
d. Biological treatment process configurations, including auxiliary facilities for aeration, mixing, and sedimentation.	
e. New developments including unsteady-state analysis, use of purified oxygen, rotating fixed-surface growth, etc.	
2. Sedimentation, Clarification and Thickening (9 lectures)	Weber, ² Ch. 3, 12
a. Flow regimes for gravity settling, including free-falling particles, hindered settling and zone settling.	
b. Solids flux concepts and design methods.	
c. Differentiation between requirements for clarification vs. those for thickening.	
d. Integration of sedimentation vessel design with the biological treatment reactors.	
e. Tube-settler operation.	
3. Precipitation (9 lectures)	Weber, ² Ch. 2
a. Physical chemistry of ionic equilibria.	Stumm and Morgan, ³ Ch. 5, 8, 10
b. Effect of complexing agents.	
c. Use of pH-solubility diagrams.	
d. Statistical approaches for application of laboratory or pilot data to design.	
1. Oxidation-Reduction (6 lectures)	Weber, ² Ch. 8
a. Stoichiometry for common oxidants and reducing agents.	Stumm and Morgan, ³ Ch. 7
b. Reaction rate concepts.	
c. Oxidation-Reduction Potential and relations to electrochemical processes.	

dustrial wastewater treatment, to change inorganic pollutants either directly into innocuous forms (e. g., conversion of cyanides to CO_2 by chlorine oxidation) or into another form more tractable for treatment by conventional processes (e. g., reduction of chromates to trivalent chromium ions prior to precipitation of the insoluble $\text{Cr}(\text{OH})_3$).

LABORATORY PROGRAM

FOUR EXPERIMENTS ARE OFFERED with "Wastewater Engineering" on Biological Waste Treatment, Biological Respirometry, Sedimentation and Thickening, and Precipitation Processes. They have been selected and developed, based on the following criteria:

- The experiments must complement and relate directly to the course material.
- They must be realistic in the sense that data obtained from the experiment can be applied to design problems discussed in class.
- It is important that the experiments are carried out in a manner that allows students to participate and, thus, obtain "hands on" experience.
- The experiments should be organized into laboratory sessions no longer than about three hours.
- The students should be able to operate all necessary equipment without extensive training.

BIOLOGICAL TREATMENT

This experiment provides students with the opportunity to measure the reaction rates and stoichiometry of the bio-oxidation of a particular waste. They obtain the data by monitoring changes in organic substrate and suspended solids concentrations occurring for a mixed culture in a batch reactor. This permits the experiment to be completed in one laboratory period. A continuous reactor at steady state would provide only a single rate measurement during the same time span.

Careful preparation is needed beforehand to assure that the rates measured in this experiment approximate those of a full scale system. The mixed culture must be acclimated to the waste and mode of operation, and the average bacteria floc size should be similar to those found in full scale systems. Both acclimatization and classification of flocs by size can best be carried out in a continuous system in which bacteria are recycled.* These steps require a separate reactor and consume more time and attention than the experiment itself. For example, during acclimatization care must be taken to avoid filamentous growth on the walls of small reactor vessels.

Such growth represents an active bacteria population which is significant on the laboratory scale but negligible in full-scale operation.

The Total Organic Carbon (TOC) or Total Carbon analyzers are the most efficient means of measuring substrate concentrations. Indeed, this experiment would not be feasible if we had to use the difficult, inaccurate and time-consuming B. O. D. or C. O. D. tests. Suspended solids (a measure of bacterial culture concentration) are monitored gravimetrically.

Students calculate yield factors and rate

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constants for substrate oxidation directly from the data obtained here. Usually the change in microbial mass during the batch experiment is not large enough to obtain a good estimate of the culture's specific growth rate. This can be better determined from measurements of sludge wasted in a continuous system (i e., either full- or bench-scale). With this additional information, students are able to: 1) select the operating level of bacteria and specify the hydraulic residence time, 2) specify sludge waste rate, and 3) determine theoretical aeration requirements for a full scale reactor.

BIOLOGICAL RESPIROMETRY

EXPERIMENTS IN RESPIROMETRY illustrate a number of points pertinent to biological waste treatment. A sample of waste is seeded with bacterial culture and then isolated in a stirred container with air or oxygen in the gas cap. Pressure changes resulting from the absorption of evolved carbon dioxide and uptake of oxygen by the culture indicate the extent of oxidation. Inexpensive, direct-reading apparatus is available commercially. (Hach Chemical Co. Model 2173), as well as more elaborate electrolytic equipment which log the data automatically.

*For experiments involving industrial wastes, a commercially available bench scale reactor-settler is recommended. (Cole Parmer: Bio-Oxidation Reactor). A more expedient approach is to use samples of a waste (e. g., primary effluent) and culture (activated sludge return) obtained from a local treatment plant.

This experiment takes a number of days to run, 3-6 days for carbonaceous oxidation only and up to 10 days for nitrification. Students are organized into teams to carry out monitoring around the clock over the desired period.

Tests carried out simultaneously on a number of containers demonstrate the effects of bacterial seeding, stirring, substrate concentration, etc. on the shape of the uptake curves. This experiment illustrates the relationships among B. O. D., C. O. D. and T. O. C. The students complete this study with a comparison of the observed uptake curves to the ideal characteristics proposed in the lectures.

SETTLING MODES

Students observe the characteristics of hindered and zone settling modes, and measure the rates of settling at each condition. The major apparatus is simply a 6" I. D. x 7 ft. high plexiglass column which is equipped with sampling ports. The batch settling tests are carried out with actual wastewater samples, (e. g., primary influent and aeration "mixed liquor"). An investigation of each condition occupies one laboratory period.

The settling rates are determined from changes in suspended-solids concentration profiles during settling. In hindered settling studies, the concentrations are measured directly. In zone-settling studies, the concentration is estimated indirectly from the sludge blanket height. Graphical methods introduced in the lectures are used to calculate the rates from these profiles. This permits students to specify the basin areas required in continuous operations. Comparative studies with and without flocculation aids would illustrate their effects on the design specifications.

PRECIPITATION PROCESS

A precipitation process of considerable local interest is removal of phosphates. Both stages of precipitation, nucleation and flocculation, can be readily investigated in a simple batch reactor in which mixing is controlled, (i. e., a jar test).

Stirring equipment designed especially for this experiment is available commercially (Phipps & Bird Stirrer). Students investigate the effects the following variables on treatment efficiency:

- Wastewater composition (e. g., solution pH, alkalinity, particulate concentration, and initial phosphorous concentration),
- Ratio of ortho- to poly-phosphates,
- Type and dosage of precipitant (e. g., lime, alum or ferric salts),

- Type and dosage of flocculant aids (e. g., anionic and cationic polymer), and
- Turbulence level (i. e., mixing intensity).

Though each test can be completed in 30 minutes, a large number of tests are required. The present state of the art is empirical, and thus the effects of the above variables must be determined for each particular waste. Also, as the composition of a waste usually varies with time, there is a further problem of determining chemical dosage which results in the desired removal over a specified percentage of the time.

Both problems require that the students apply statistical techniques discussed in class. An efficient approach to experimental design permits the relative importance of independent variables to be sorted out in a minimum number of tests. The problem of specifying suitable levels of the chemical dosage is solved by a frequency-of-occurrence analysis. Because each problem requires at least 8-10 tests to be carried out, the chemical analysis must be efficient. For example, an automated system (Technicon Autoanalyzer II) is used here to carry out phosphorus measurements.

RELATION TO OTHER COURSES

"Wastewater Engineering" is one of three graduate chemical engineering courses which deal primarily with wastewater topics. "Separation Science" deals in part with the more costly selective membrane and packed-column processes, which find application for industrial wastewater treatment either to meet stringent effluent quality requirements or for recovery byproducts. "Colloidal Systems" deals with fundamental considerations on coagulation and flocculation and on the nature of turbidity. This adds to understanding of sedimentation and precipitation processes.

These three, plus courses on "water Resources" and on "Legal, Economic and Political Aspects of Water Pollution" available through Systems Engineering provide a core program for chemical engineers specializing in wastewater. Added to traditional chemical engineering graduate courses in thermodynamics, transport phenomena and chemical reaction engineering, this provides a unique background for professional careers in development and design of treatment facilities for industrial wastewaters or for advanced municipal wastewater treatment. A measure of our success with this program is that all of our graduate students who have completed it to date are active in the area.□

REFERENCES

- ¹Busch, A. W., *Aerobic Biological Treatment of Wastewaters*, Oligodynamics Press, Houston, 1971.
- ²Weber, W. J., editor, *Physiochemical Processes for Water Quality Control*, Wiley, New York, 1972.
- ³Stumm, W. and Morgan, *Aquatic Chemistry*, Wiley, New York, 1970.

ENZYME AND BIOCHEMICAL ENGINEERING

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THE CURRENT INTENSE interest in novel methods of enzyme applications in the food, pharmaceutical, biomedical and waste treatment processes obviated the need to augment the food technology program in our department with a graduate level course in Enzyme and Biochemical Engineering. The title implies all engineering aspects; however, the essence of the course focused upon kinetics and reactor design with emphasis on immobilized enzyme systems. The course was structured to expose the graduate student and researcher to basic concepts, methodologies, and techniques in enzyme technology which would permit rational design and analysis of immobilized enzyme reactor systems and fermentor reactor design.

I. Enzyme Structure, Kinetic Action, Preparation and Immobilization and II. Enzyme and Biological Reactor Design. An attempt is made to develop an appreciation of how enzymes function, the sensitive and specific nature of enzymes and the immobilization methods recently developed which promise to make enzyme utilization in large scale process feasible. (see Table I).

The course is presented towards a first level graduate chemical engineering student with undergraduate transport phenomena, reaction engineering and mathematics through partial differential equations desirable. Preferably the student should have a background in biology and/or biochemistry. Advanced level biology and biochemistry students fare reasonably well but deficiencies in chemical engineering and mathematics courses made aspects of the second part of the course disconcerting.

Several problem assignments and a term paper with an oral presentation were the student requirements. Readings in the various topics were encouraged.

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DISCUSSION OF COURSE MATERIAL

Enzyme Structure, Kinetic Action, Preparation and Immobilization

THE FIRST THREE sections of Part I introduces the student to the biochemistry of enzymes, the classes of reactions which enzymes catalyze and the kinetic mechanism postulated to describe the enzyme action. The biochemistry of proteins is discussed starting with the amino acids and how enzyme specificity is determined by

TABLE I

Enzyme and Biochemical Reaction Engineering Course Outline

- Part I. Enzyme Structure, Kinetic Action, Preparation and Immobilization
 - A. Structure of Enzymes
 - B. Classes of Enzyme Reactions
 - C. Enzyme Kinetics
 - D. Enzyme Production
 - E. Enzyme Isolation and Purification
 - F. Enzyme Immobilization Methods
- Part II. Enzyme and Biological Reactor Design
 - A. Ideal Batch, Tubular and CSTR Reactors
 - B. Ideal Reactor Concepts with Enzyme Kinetics
 - C. Fermentation Kinetics and Reactor Design
 - D. Physical and Chemical Rate Processes in Heterogenous Immobilized Enzyme Systems
 - E. Diffusional Influences in Hollow Fiber Catalysts
 - F. Immobilized Enzyme Deactivation and Parameter Determination
 - G. Design of Immobilized Enzyme Reactors
- Part III. Student Presentation of Term Papers.

its particular sequence of amino acid residues and higher order structure. The primary, secondary, tertiary and quaternary structures of proteins are discussed with some detail given to the geometry of the peptide bond, α -helix and pleated sheet structures, and the various types of bonds which determine higher order structures.

Classes of enzyme reactions such as oxidoreductases, transferases, hydrolases, lyases, isomerases and ligases are then presented. Appropriate time is devoted to enzyme kinetics. Michaelis-Menten theory of enzyme substrates complex is presented and then applied to derive the reaction velocities for competitive, noncompetitive, substrate and product inhibition kinetics. Temperature, pH effects and enzyme inactivation effects are delineated. Methods of the determination of rate coefficients are illustrated. Examples of starch hydrolysis, glucose isomerization, and lypase glycerolysis are employed to indicate enzyme kinetics of current interest. Various references (1-8) were helpful in the preparation of the material.

Methods of enzyme production, isolation and purification then followed. Examples of the various plant, animal and micro-organism sources of enzymes were presented with specific attention given to the last source. Specific examples (9-11) illustrated how optimum yields were obtained in these fermentations. Isolation and purification was presented in three stages of (a) cell removal, disruption or extraction, (b) initial fractionation techniques, and (c) high resolution techniques (see Table II). Adequate references exist (12-30) which delineate specific aspects and entire enzyme production schemes.

Immobilized enzymes was the last section discussed in Part I. Excellent reviews are available (31-36). The methods discussed were covalent attachment to water insoluble supports, covalent intermolecular crosslinking, adsorption, containment within devices and entrapment with cross-linking polymers.

Enzyme and Biological Reactor Design

Material and energy balances for ideal homogeneous batch, CSTR and plug flow reactors with enzyme and fermentation kinetics are presented in the first three sections. Michaelis-Menten kinetics with and without substrate inhibition are employed. Effects of nonideal flow and possibilities of multiple steady states for substrate inhibition kinetics are introduced. The Monod model for fermentation kinetics is presented. Batch and continuous fermentations are discussed with some attention to washout phenomena, multistaged reactors, nonideal flow and micro-mixing effects. Models of hydrocarbon fermentation are present-

TABLE II

Enzyme and Biochemical Reaction Engineering Enzyme Isolation and Purification

(Subsection E of Part I).
Introductory Comments, Enrichment, Yields, Lab. Results.
Solid-Liquid Separation
 Centrifugation
 Filtration
Disruption of Microorganisms
 Nonmechanical
 Mechanical
Initial Fractionation Procedures
 Salt Precipitation
 Solvent Precipitation
High Resolution Techniques
 Electrophoresis
 Ultrafiltration
 Gel Filtration—Gel Chromatography
 Affinity Chromatography

The course introduces the student to the biochemistry of enzymes and merges the techniques of chemical reactor engineering with immobilized enzyme and biochemical kinetics and exposes methods of reactor design for these systems.

ed which consider microbial sorption to/from droplets, growth on the droplet surface and within broth, droplet size distribution and mixing, and oxygen absorption. Chemical reaction engineering texts and various other references were employed (15, 37-42).

The interaction of chemical and physical rate processes are presented for the single particle. Various limiting cases such as external mass transfer with surface reaction, diffusional resistances and reaction within the particle are discussed and isothermal effectiveness factors are introduced. Diffusional influences in membrane catalysts for planar, cylindrical (hollow fiber) or spherical geometry are also formulated for Michaelis-Menten kinetics. Overall rate expressions for single particles and membranes are formulated. Various references employed are (43-45). To complete the discussion, a formulation of enzyme kinetics with inactivation is presented for various modes of deactivation. Deactivation parameter estimations for various fluid-solid reactor configurations as discussed in Levenspiel (37) are extended to Michaelis-Menten kinetics and examples are presented.

The performance equations are employed with the rate expressions developed to predict conversion for fixed

bed immobilized enzyme reactors, slurry reactors with dispersed immobilized enzyme, and tubular membrane reactors. Modes of reactor operation for deactivating immobilized enzymes to maximize production are discussed for the glucose isomerase reaction. A fixed bed reactor with plug flow of fluids is considered and varying temperature policy (44) or substrate flow rate is employed to maximize yields and/or maintain constant product quality. □

REFERENCES

- M. Dixon and E. C. Webb, *Enzymes*, 2nd Ed., Academic Press, Inc. New York, 1964.
- S. Bernhard, *The Structure and Function of Enzymes*, W. A. Benjamin, Inc. New York, 1968.
- H. Gutfreund, *An Introduction to the Study of Enzymes*, John Wiley, Inc. New, 1965.
- J. M. Reiner, *Behaviour of Enzyme Systems*, Burgess Publishing Company, Lib. of Cong. Cat. No. 59-8042 Minneapolis 15, Minn. 1959.
- K. J. Laidler, *The Kinetics of Enzyme Action*, Oxford University Press, London, 1958.
- John Westley, *Enzyme Catalysis*, Harper and Row, New York, 1969.
- Notes from CES 7001, *Enzyme Technology and its Engineering Applications*, June 1-5, 1970 Univ. of Penn. Phila., Pa.
- L. L. Tavlarides, "Enzyme Kinetics Lectures," presented at Moffet Technical Center, CPC, International, Argo, Illinois.
- W. W. Windish, N. S. Mharte, "Microbial Amylases," *Advances in Applied Microbiology*, Vol. 7, p 273-304, (1965).
- K. Mizusawa, E. Ichishima, F. Yashida, "Production of Thermostable Alkaline Proteases by Thermophilic *Streptomyces*," *Applied Microbiology*, V17n3, 366-371, (1969).
- L. Nyiri, "Manufacture of Pectinases," *Process Biochemistry*, V3n8, 27 (1968), Morgan-Grampian (Publishers) Ltd.
- S. Schwimmer, A. B. Pardee, "Principles and Procedures in the Isolation of Enzyme," *Advances in Enzymology*, V14, p 375.
- S. Aiba, S. Kitai, N. Ishida, *J. of Gen. and App. Microbiol.* V8, 109 (1962).
- N. C. Mahoney, *Process Biochemistry*, V3n9, 19 (1968).
- S. Aiba, A. E. Humphrey, N. F. Millis, *Biochemical Engineering*, Academic Press, N. Y., 1965.
- C. Ambler, *J. of Biochem. and Microbiochem. Tech. and Engr.*, V1, 185 (1959).
- Nepperas, E. A., D. E. Hughes, *Biotech. & Bioeng.*, V6 247-70 (1964).
- J. W. T. Wimpenny, *Process Biochem.* V2n7, 41 (1967).
- J. T. Edsal, "Plasma Proteins and Their Fractionation," *Adv. in Protein Chem.* V3, 408 (1947).
- M. Dixon and E. C. Webb, "Enzyme Fractionation by Salting Out: a Theor. Note," *Adv. in Protein Chem.*, V17, 197 (1963).
- B. A. Askonas, *Biochem. J.* V48, 42 (1951).
- M. Bier, *Electrophoresis Theory, Methods and Applications* Academic Press, Inc. New York, N. Y. 1959.
- M. Bier, *Electrophoresis Theory, Methods and Applications*, Academic Press, Inc., New York, N. Y. (1967).
- M. K. Joustra "Gel Filtration on Agarose Gels," *Modn. Sepn. Methods of Nacsomolecules and Particles*, *Prog. in Sepn. and Purification*, Vol. 2, 183 (1969).
- T. C. Laurent, B. Obrink, K. Hellsing A. Wasteson "On the Theoretical Aspects of Gel Chromotography," *Modn. Sepn. Methods of Macromolecules and Particles*, *Prog. in Sepn- and Purification* Vol. 2, 199-218, (1969). Wiley.
- P. Cuatrecasas, *Adv. in Enzymol.* V36, 29 (1972).
- P. H. Clarke and M. D. Lilly, "Enzyme Synthesis During Growth," in 19th Symposium of Society for General Microbiology, (1969).
- R. Davies, "Microbial Extracellular Enzymes, Their Uses and Some Factors Affecting Their Formation," *Biochemistry of Industrial Microorganisms* ed. by C. Rainbow and A. M. Rose, Academic Press, 1963.
- R. Luedeking, "Fermentation Process Kinetics," *Biochemical and Biological Engineering Science*, Vol. I, ed. by N. Blakebrough, Academic Press, 1967.
- J. W. Richards, "Economics of Fermentation Operation, Parts I and II," *Process Biochemistry*, Vol. 3, Nos. 5 & 6 1968.
- I. H. Silman, and E. Katchalski, *Ann. Rev. Biochem.* 35, 873.
- L. Goldstein, In *Methods of Enzymology XIX*. G. E. Perlman and L. Lorand Ed., Academic Press, New York, p. 935, (1970).
- E. Katchalski, I. Silman and R. Goldman, *Adv. Enzymol.* 34, 445, (1971).
- K. Mosbach, *Scientific American* 224, 26, (1971).
- R. Goldman, L. Goldstein, and E. Katchalski, In *Biochemical Aspects of Reactions on Solid Supports*, Stark, G. R., Ed., Academic Press, New York, p. 1., (1971).
- O. R. Zaborsky, *Immobilized Enzymes*. CRC Press, Cleveland, Ohio, (1973).
- O. Levenspiel, *Chemical Reaction Engineering*, 2nd Ed. John Wiley & Sons, Inc., New York, N. Y. (1972).
- R. Artis, *Introduction to the Analysis of Chemical Reactors*, Prentice Hall, Inc., Englewood Cliffs, N. J., (1965).
- J. M. Smith, *Chemical Engineering Kinetics*, 2nd Ed. McGraw-Hill Book Co., New York, N. Y. (1970).
- L. T. Fan, B. I. Tsai, and L. E. Erickson, "Simultaneous Effect of Macromixing and Micromixing on Growth Processes," *AICHE, J.* 17 (3), 689 (1971).
- M. Stamatoudis and L. L. Tavlarides, "Model of Hydrocarbon Fermentation," paper presented at 75th National AIChE Meeting, Detroit, Mich., June 1973.
- S. P. O'Neill, M. D. Lilly, P. N. Rowe "Multiple Steady States in CFST Enzyme Reactors," *Chem. Eng. Sci.* V26, 173 (1971).
- R. Aris *Chem. Eng. Sci.* V6, 282 (1957).
- J. Crank, *Math. of Diffusion*, Clarendon Press. Oxford, England, 1956.
- P. R. Roney, "Multiphase Catalysis II Hollow Fiber Catalysis," *Biotechnology and Bioengineering*, V13, 431, (1971).
- W. R. Haas, L. L. Tavlarides, W. J. Wnek, "Optimal Policy for Reversible Reactions with Deactivation: Applied to Enzyme Reactors," *AICHE, J.*, July, 1974.

The inside word on the outside world.

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JOHN H. SEINFELD, California Institute of Technology. 1975, 400 pages (tent.), \$18.50 (tent.).

Here is a quantitative and rigorous approach to the basic science and engineering underlying the air pollution problem. The most comprehensive single book available on the subject, it provides an in-depth treatment of air pollution chemistry atmospheric transport processes, combustion sources and control methods.

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EMIL CHANLETT, University of North Carolina at Chapel Hill. 1973, 608 pages, \$17.50. Solutions Manual

ENVIRONMENTAL PROTECTION is man-centered. This book describes the rationale for the management and protection of our land, air, water, and energy resources. The consequences of mismanagement of the major environmental components are examined at three levels: 1) effects on health; 2) effects on comfort, convenience, efficiency and esthetics; and 3) effects on the balance of ecosystems and of renewable resources. Although scientific and engineering principles are stressed, the material covered is presented in a clear, non-mathematical manner to facilitate a broad understanding by relatively divergent groups.

ENVIRONMENTAL SYSTEMS ENGINEERING

LINVIL G. RICH, Clemson University. *McGraw-Hill Series in Water Resources and Environmental Engineering*. 1973, 405 pages, \$17.50. Solutions Manual

While covering a broad spectrum of environmental topics, the focus is on the system as a whole and how its components interact rather than the components themselves. This systems approach is used in formulating and analyzing environmental phenomena, as well as in the selection and design of engineered facilities needed for controlling the environment. Although water environment is considered in greatest detail, also included are air pollution and its control, solid waste management and radiological health. The mathematics of systems analysis and computer solutions is used extensively.

SYSTEMS ANALYSIS AND WATER QUALITY MANAGEMENT

ROBERT V. THOMANN, Manhattan College. 1972, 286 pages (tent.), \$19.50 (tent.).

Using both mathematical models of environmental responses and management and control schemes, the text provides a series of analytical tools for describing and forecasting the effects of the surrounding environment on the water quality of a stream or estuary, presents information on water quality criteria and wastewater inputs, establishes a point of departure for evaluating the worth of water quality improvement projects and discusses the benefits of applying cost/benefit analysis to engineering.

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HAL B. H. COOPER, JR., University of Texas at Austin, and AUGUST T. ROSSANO, JR., University of Washington. 1971, 278 pages, \$13.50.

A discussion of principles and methods used for testing of gaseous and particulate materials being emitted from industrial, combustion and other sources is presented in this informative text. Organized to give the reader a logical presentation of the steps taken in source testing, the book includes an extensive examination of the equipment, methodology, sampling, and analytical techniques in use for gaseous and particulate particles.

AIR POLLUTION

H. C. PERKINS, University of Arizona. 1974, 407 pages, \$15.50. Solutions Manual

To date, this is the only truly engineering-oriented text on the subject that draws upon the student's background in analyzing and solving problems in air pollution. The treatment is sufficiently detailed to enable chemical, mechanical, and sanitary engineering students to solve a variety of problems. A complete discussion of the global effects of air pollution is included along with numerous applications-type problems.

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Important changes in this revision include a consolidation and unification of material resulting in fewer chapters, the addition of a large number of worked examples, extensive use of SI units, and use of the same sign conventions for both work and heat. Also featured are an expanded treatment of refrigeration and power cycles and extension of the discussion on flow processes to include adiabatic flow processes, especially transonic flows.

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MERTON C. FLEMINGS, Massachusetts Institute of Technology. 1974, 580 pages, \$19.50. Solutions Manual

Professor Flemings has written the only book that treats the engineering side of solidification processes in depth. Unique in its application of solidification theory, **SOLIDIFICATION PROCESSES** builds on the foundation of heat flow, mass transport and interface kinetics. Similarities as well as differences between processes are highlighted, and among the processes considered are crystal growing, shape casting, ingot casting, growth of composites and splat cooling.

MASS TRANSFER

THOMAS K. SHERWOOD, ROBERT L. PIGFORD, and CHARLES R. WILKE, all of the University of California, Berkeley. 1975, 512 pages (tent.), \$18.50 (tent.).

Compared to the 1952 version *Absorption and Extraction*, this volume is substantially more sophisticated, providing a much broader coverage of mass transfer. Emphasis is on the practical aspects and real problems that demand an understanding of theory. Yet, theoretical derivations are minimized by explicit citation of over 1,100 contemporary references.

PRINCIPLES OF THERMODYNAMICS

JUI SHENG HSIEH, New Jersey Institute of Technology. 1975, 500 pages (tent.), \$16.50 (tent.)

A clear and unified treatment of various thermodynamic systems, this new text illustrates the wide range of applicability of the basic laws of thermodynamics. Beginning with a comprehensive review of the first and second laws, the text examines thermodynamic relations for single- and multi-component compressible systems; stability; phase and chemical equilibrium; thermodynamics of elastic system, interfacial-tension system, magnetic system, and electric system; cryogenics; and the third law and negative Kelvin temperatures.

INTRODUCTION TO METALLURGICAL THERMODYNAMICS

DAVID R. GASKELL, University of Pennsylvania. *McGraw-Hill Series in Materials Science and Engineering*. 1973, 550 pages, \$19.50.

Here is a modern text which details the thermodynamics of high temperature systems encountered in metallurgy, via systematic development of the criteria governing equilibria in metallurgical reaction systems. Use of the thermodynamic method is demonstrated by an extensive illustration program using, as examples, real systems which have been carefully selected to illustrate the thermodynamic principles involved.

INTRODUCTION TO CHEMICAL ENGINEERING THERMODYNAMICS, Third Edition

J. M. SMITH, University of California at Davis, and H. C. VAN NESS, Rensselaer Polytechnic Institute. *McGraw-Hill Series in Chemical Engineering*. 1975, 672 pages (tent.), \$16.50 (tent.).

Including a new chapter on solution thermodynamics, the third edition of this successful fundamentals text maintains a unified treatment of thermodynamics from a chemical engineering viewpoint. The chapters on phase and chemical-reaction equilibrium have been rewritten and expanded in order to present a coherent exposition of these topics.

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SEPARATION PROCESSES

C. JUDSON KING, University of California, Berkeley. *McGraw-Hill Series in Chemical Engineering*. 1971, 736 pages, \$19.50. Solutions Manual

This text stresses the many common aspects of the functioning and analysis of different separation processes, such as distillation, absorption, and extraction. Modern computational techniques for single and multistage separations are considered with the emphasis on an understanding of the various conditions which favor different computational approaches.

THE INTERPRETATION AND USE OF RATE DATA

STUART W. CHURCHILL, University of Pennsylvania. 1974, 510 pages, \$19.50. Solutions Manual

Professor Churchill offers a completely new and unique treatment of the rate processes which is unified and generalized in terms of both procedures and processes. An elementary, basic coverage of chemical reactor design, momentum transfer, heat transfer and component transfer is provided. Discussion focuses on raw, experimental data rather than on hypothetical processes and data.

MOMENTUM, HEAT AND MASS TRANSFER, Second Edition

C. O. BENNETT, University of Connecticut, Storrs and J. E. MYERS, University of California, Santa Barbara. 1974, 810 pages, \$17.95. Solutions Manual

Combining a rigorous approach to fundamentals with an extended treatment of practical problems, this revision illustrates basic ideas by applications to industrial processes. The reader is offered an understanding of the principles which govern the operation and design of chemical and physical processes in industry. Mathematics through dif-

ferential equations is used freely, but empirical procedures are also described. New appendixes give sufficient data so that the problems can be done without reference to a handbook. In addition, 50% of the problems are new.

THERMODYNAMICS, Second Edition

JACK P. HOLMAN, Southern Methodist University. 1974, 608 pages, \$16.50. Solutions Manual. Self-Study Cassettes, \$65.00. Self-Study Guide, \$3.50.

All standard thermodynamics topics can be covered from either the classical or statistical viewpoint or from any desired integration of the two with this book. In this revision there is a 60% expansion of classical thermodynamics and applications. Many new examples and problems worked in both fps and SI units have been added.

HEAT TRANSFER, Third Edition

JACK P. HOLMAN, Southern Methodist University. 1972, 496 pages, \$15.50.

This elementary text offers a brief and concise treatment of all phases of heat transfer. New features include chapters on environmental problems, emphasis on numerical techniques in conduction problems and an increase in text examples.

AIR POLLUTION CONTROL: GUIDEBOOK FOR MANAGEMENT

AUGUST T. ROSSANO, JR., University of Washington, and HAL B. H. COOPER, JR., University of Texas at Austin. 1969, 214 pages, \$21.50.

The book provides a comprehensive and balanced treatment of the complex technical and administrative nature of air pollution problems. All major elements of the field are included to provide both a text and background reference of the subject in one volume.

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FALL 1974



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THE SCIENCE OF SYNTHETIC AND BIOLOGICAL POLYMERS

CURT THIES

*Washington University
St. Louis, Missouri 63130*

THE SCIENCE OF SYNTHETIC and Biological Polymers is a one semester (15 weeks) introductory graduate polymer course offered at Washington University that consists of three hours of lecture per week and carries three hours of credit. The material presented is designed to be of value to a range of engineering students including those in the materials science and biomedical engineering programs. For many students, this is the only polymer course they take. Accordingly, I try to cover a reasonably broad spectrum of material. The depth of presentation is designed to be sufficient for the students to appreciate the theoretical principles of polymer science, but it is not sufficient for them to be polymer specialists.

Because the scope of contemporary polymer science has become so broad, a one semester course can never cover more than a small fraction of the knowledge available. Thus, I am highly selective about what is presented. The choice of subject matter is prejudiced by my industrial research experience. Regardless of where today's students ultimately work, I am convinced that they will encounter many of the same types of problems that I encountered. These include problems associated with selection of polymers for a specific application, deterioration or change in polymer properties with use, pushing a polymer product to the limits of its capabilities, and assuming lot-to-lot reliability of polymer-containing products. All of these problems constantly plague polymer users. Accordingly, I slant the course material toward polymer characterization, selection, properties and weaknesses. Being a physical chemist, I take a physico-chemical approach to all material presented. The fundamental principles discussed are kept as simple and logical as I can make them. I try frequently to introduce practical

examples into the lecture material thereby illustrating the various topics discussed. My entire goal is to maximize long-term retention of useful knowledge of polymers by the students.

COURSE CONTENT

TABLE 1 CONTAINS an outline of the course material. I start with polymer nomenclature and follow this with a discussion of the chemistry involved in preparing various polymers. I then cover polymer characterization and polymer structure/property relationships. Polyelectrolytes and proteins are treated after polymer solution properties. In addition, I deliberately try to include illustrative examples of biological or water-soluble polymers throughout the course. This is done primarily for the benefit of the biomedical students, but the other students benefit too, since industrial uses of water-soluble polymers are steadily increasing. As noted previously, all topics are approached from a polymer user viewpoint. Basic principles are stressed constantly, but the course has a definite practical orientation. In order to visualize the subject matter given, it is appropriate to discuss in more detail the sequence of topics listed in Table I.

Choice of subject matter is prejudiced by my industrial research experience... I slant the material toward polymer characterization, selection, properties and weaknesses... a physical chemist, I take a physico-chemical approach to all material presented.

The first topic is nomenclature. At times, one tends to look upon this as a trivial topic. However, consistent with my efforts to stress fundamentals, I spend several lectures on nomenclature. These introductory lectures also enable me to introduce the basic concepts of polymer structure.

Table I
COURSE OUTLINE

- I. Nomenclature
- II. Polymer Chemistry
 - A. Kinetics of polycondensation reactions
 - B. Kinetics of free radical polymerization
 - C. Copolymerization kinetics
 - D. Ionic polymerization reactions
 - E. Epoxy and urethane curing reactions
- III. Polymer Characterization
 - A. Solution Properties
 - 1. Solubility Behavior
 - 2. Fractionation
 - 3. Molecular Weight Determination
 - B. Polyelectrolytes and Proteins
 - C. Bulk Properties of Polymers
 - 1. The Glass Transition and Crystalline Melting Point
 - 2. Viscoelasticity
 - 3. Rubber Elasticity
- IV. Polymer Structure/Property Relationships
 - A. Factors That Affect the Glass Transition
 - B. Factors that Affect Crystallinity
 - C. Structural Analysis of Widely Used Plastics

The students are exposed to the difference between linear, branched, and crosslinked polymers, the meaning of stereoregularity, etc. I do my best to cover a broad spectrum of polymer terms in common use. The beauty and complexity of biological polymers from a structural viewpoint is introduced too. I also expect the students to learn the chemical structures of a number of widely used commercial polymers (e. g., polyethylene, poly(vinyl chloride), etc.). To me, knowing the chemical structures of a number of polymers provides a mental picture of how various polymers differ structurally and lays the groundwork for more meaningful discussion of polymer properties later in the course.

PREPARING POLYMERS

FOLLOWING NOMENCLATURE, I spend considerable time going over the chemistry involved in preparing various types of polymers. This takes about 25% of the total semester lecture time. I feel that spending so much time on polymer chemistry is easily justified, because polymers are constantly used under conditions where they depolymerize, oxidize, and/or crosslink. All of these reactions cause profound changes in polymer properties and occur when polymers deteriorate with use. By stressing to the students how polymer molecules are assembled, it is logical to point out simultaneously how various polymerization reactions can either be reversed



Curt Thies has been an Associate Professor of Chemical Engineering at Washington University since January 1973. He is a native of Michigan. He received a B.S. in Chemistry from Western Michigan University (1956); M.S. from the Institute of Paper Chemistry (1958); and Ph.D. in the Physical Chemistry of Polymers with a minor in Chemical Engineering from Michigan State University (1962). Prior to joining Washington University he had an industrial career culminating with the position of Head of the Polymer/Microencapsulation Research Section of NCR. His research and teaching interests are in the areas of colloid and surface behavior of polymers, microencapsulation, and polymer mixtures.

to cause depolymerization or altered to cause crosslinking.

Much of the chemistry discussed relates to condensation, free radical, and ionic polymerization processes. However, I also discuss the various mechanisms by which epoxy and urethane resins are cured. I spend time on these latter two families of polymers because: 1. they are widely used in situations engineers are likely to encounter (e. g., adhesives, foams, and composite materials); 2. it gives me an opportunity to go over the concept of crosslinking and thermoset resins in some detail. The level of organic chemistry presented is always relatively elementary, but I feel that it suffices to indicate to the students how the major types of polymerization reactions differ. I stress polymerization kinetics. From the kinetic approach, the students learn to appreciate that polymer chain length, rate of chain growth, etc., differ for the various polymerization process. I try to note how these important parameters can be controlled to thereby give the polymer producer a great degree of control over tailoring polymer molecules for specific end uses.

The kinetic expressions developed for free radical copolymerization reactions are also discussed. Many copolymers are of significant commercial importance and the students should have a grasp of the fundamental principles that poly-

mer producers use to minimize or avoid formation of compositionally heterogeneous copolymers. The discussion of copolymer kinetics also helps the students to appreciate the sequence in which monomers are added to a growing polymer chain and how differences in the sequence of monomer addition lead to gross changes in polymer structure with concomitant changes in properties.

POLYMER CHARACTERIZATION

FOLLOWING THE PRESENTATION of polymerization reactions, I devote a number of lectures to polymer characterization. The techniques discussed fall into two broad categories: those that utilize polymer solution properties and those that are based on polymer bulk properties. I begin with the former. One of the first points I try to make is that few commercial polymers are pure. Polymer manufacturers inevitably add to their products a range of additives like light stabilizers, anti-oxidants, processing aids, etc. Toxicity of these additives is of critical importance to those interested in biomedical applications because they can be leached from the polymer matrix during use. Thus, I stress that the first step to take in characterizing a polymer sample is to find out what is present, including the additives. Infrared spectroscopy is a convenient means of doing this. In the case of complex mixtures, the various components are separated by differences in solubility. This then leads into a general discussion of polymer solubility behavior. I stress that solubility in a range of solvents and over a range of temperatures not only enables one to separate complex mixtures and fractionate polymers into different molecular weight fractions, but also provides insight into the molecular structure of a polymer (e. g., crystalline polymers are more insoluble than noncrystalline polymers, crosslinked polymers are insoluble in all solvents, etc.).

After discussing polymer solubility, I swing into the theory underlying the commonly used methods of determining polymer molecular weight and the meaning of the various molecular weight averages. Included in the presentation is an introduction to gel filtration and gel permeation chromatography. I spend only about three to four lectures on these topics, because I am simply trying to get the students to appreciate how polymer molecular weights differ from those of non-polymeric species. I also am constantly warning them always to specify what molecular weight

average they mean when they quote the molecular weight of a polymer.

At this point, I begin to discuss what addition of ionic groups to a polymer chain does to the polymer and thereby develop the concept of polyelectrolytes. The discussion of polyelectrolytes, in turn, serves as a lead into a discussion of proteins. I spend several lectures presenting proteins and glycoproteins from a polymer chemist's viewpoint. The reactions that proteins undergo are not considered. I focus exclusively upon their primary, secondary, tertiary, and quaternary structure and the influence that intra-or inter-molecular bonding has upon each of these structures.

After proteins, I treat bulk polymer properties. The concept of glass transition (T_g) and melting point (T_m) is stressed and attention is focused upon how these events affect polymer properties. This involves showing how a polymer's modulus changes as one passes through T_m and/or T_g . The influence of crosslinking, crosslink density,

The students are exposed to the difference between linear, branched and crosslinked polymers, the meaning of stereoregularity, etc. . . . The beauty and complexity of biological polymers from a structural viewpoint is introduced.

and degree of crystallization on the modulus/temperature curves is used to illustrate how structural and/or morphological changes in a polymer influence its properties. At this point, the structural requirements for a polymer to develop crystallinity and the concept of folded-chain polymer crystals are also treated. This is followed by a discussion of the viscoelastic properties of polymers which involves going through the Voigt, Kelvin, and four-parameter models of viscoelasticity. The thermodynamics of rubber elasticity is also covered. Particular emphasis is placed upon the key structural features of polymers needed for elastic behavior.

The final portion of the course is devoted to a discussion of polymer structure/property relationships. Structural factors that favor increased T_g or T_m of a polymer are considered. The effect of copolymerization upon T_g or T_m of a polymer are considered. The effect of copolymerization upon T_g and the degree of crystallinity

exhibited by a polymer is also discussed. I try to show how polymer structure plays a key role in determining what properties a polymer has. This then determines the applications for which a polymer is suited. In order to drive this point home, I like to list the T_g and T_m values for a number of widely used polymers. I then go over the structural features of each polymer and indicate how these have affected its applications.

SOURCE MATERIAL

The required text for the course is Billmeyer's *Textbook of Polymer Science* (Second Edition, John Wiley and Sons, Inc., New York, N. Y., 1971). I also have developed a set of lecture notes for parts of the course and pass these out to the students. The sequence of lecture material presentation that I favor differs significantly from that used by Billmeyer. Since a wide spectrum of subjects is covered, I also find that I like to supplement Billmeyer's text with additional material taken from the reference texts listed in Table II. Thus, I either formulate by own problems, turn to the example problems in Rosen's text, or give the homework problems in Rodriguez's book. My supply of problems is steadily increasing, but I never have enough. I favor assigning a range of problems that require relatively little time to solve rather than giving a limited number of problems that require considerable time to solve. This exposes the student to a broader range of problem situations.

CLASSROOM APPROACH

INSO FAR AS THE LECTURES are concerned, I try to provoke class participation by routinely asking lots of questions during the lectures. These are addressed to the class in general (i. e., anyone can volunteer an answer) and tend to be practical in nature. The questions are designed to establish dialogue between the students and myself during class. In this manner, I become more aware of what concepts they are not grasping well and can then spend more time on these. I also try to constantly relate my own experiences with polymers to them and warn them of some of the polymer problems that they are likely to encounter.

This past year, I was assisted in the course by Dr. Lawrence Nielsen, a Senior Scientist in the Corporate Research Department of the Monsanto Company and Affiliate Professor in the Chemical Engineering Department at Washington University. He is an experienced polymer physicist specializing in the mechanical properties of polymers and handled the lectures that dealt with this aspect of polymer science. During his lectures, the students were exposed to a concise

Table II

TEXTS FROM WHICH SUPPLEMENTAL COURSE MATERIAL IS DRAWN

Text	Supplemental Material Used
Flory, P. J., "Principles of Polymer Chemistry," Cornell University Press, Ithaca, New York, 1953.	Kinetics of polycondensation plus rubber elasticity.
Saunders, K. J., "Organic Polymer Chemistry," Chapman and Hall, London, England, 1973.	Organic polymer chemistry, including ionic polymerization processes and cure of epoxy and urethane resins.
Rosen, S. L., "Fundamental Principles of Polymeric Materials for Practicing Engineers," Barnes and Noble, Inc., New York, N. Y. 1971.	Primarily viscoelasticity. I also make extensive use of the example problems given throughout the text.
Tobolsky, A. V., "Properties and Structure of Polymers," John Wiley & Sons, Inc. New York, N. Y., 1960.	Factors affecting the glass transition, viscoelasticity.
Neurath, H., "The Proteins," Second Edition, Academic Press, New York, N. Y., 1965.	Structure of Proteins.
Rodriguez, F., "Principles of Polymer Systems," McGraw-Hill Book Co., New York, N. Y., 1970.	Homework problems.
Miller, M. L., "The Structure of Polymers," Reinhold Publishing Corp., New York, N. Y., 1966.	Polyelectrolytes and free radical polymerizations.

survey of the mechanical property behavior of polymers. The choice of relevant material presented was something only a seasoned expert could do and greatly strengthened the overall content of the course.

CONCLUSION

Before concluding, I wish to note that the content and arrangement of a course like this one is subject to constant modification. I am trying to increase the learning efficiency of the students without forcing too much knowledge on them too quickly. One means of doing this involves improving my style of delivery, especially for those topics which the students seem to consistently have greatest difficulty. My approach is to simplify the presentation as much as feasible. Furthermore, I am increasing the number of notes to be handed out before a lecture is given. In this manner, I hope to devote more of the lecture to class discussion. Only time will tell how successful these efforts are. □

SOLID-STATE PROCESS TECHNOLOGY: Donaghey

Continued from page 167.

- Technology*, Prentice-Hall, Inc., Englewood Cliffs, N. J., 1972.
3. R. A. Swalin, *Thermodynamics of Solids*, John Wiley and Sons, New York, N. Y., 1962.
 4. N. N. Greenwood, *Ionic Crystals, Lattice Defects and Nonstoichiometry*, Chemical Publishing Co., Inc., New York, N. Y., 1970.
 5. K. Nassau, "The Chemistry of Laser Crystals," in *Applied Solid State Science, Advances in Materials and Device Research*, R. Wolfe and C. J. Kriersman, eds., Vol. 2, Academic Press, New York, N. Y., 1971, PP. 173-299.
 6. M. Zief and R. Speights, eds., *Ultrapurification, Methods and Techniques*, M. Dekker, New York, N. Y., 1972.
 7. H. Schafer, *Chemical Transport Reactions*, Academic Press, New York, N. Y., 1964.
 8. W. G. Pfann, *Zone Melting*, John Wiley and Sons, Inc., New York, N. Y., 2nd Edition, 1966.
 9. R. A. Laudise, *The Growth of the Single Crystals*, Prentice-Hall, Inc., Englewood Cliffs, N. J., 1972.
 10. R. L. Parker, "Crystal Growth Mechanisms: Energetics, Kinetics and Transport," in *Solid State Physics, Advances in Research and Applications*, H. Ehrenreich, F. Seitz and D. Turnbull, eds., Vol. 25, Academic Press, New York, N. Y., 1970, pp. 152-299.
 11. R. M. Burger and R. P. Donovan, eds., *Oxidation, Diffusion and Epitaxy*, Prentice-Hall, New York, N. Y., 1967.
 12. S. A. Shaikh, "Chemical Vapor Deposition of GaAs_{1-x}P_x, Reactor Design and Growth Kinetics," M. S. Thesis, University of California, Berkeley, September 1972.
 13. H. R. Camenzind, *Electronic Integrated Systems Design*, Van Nostrand Reinhold Co., New York, N. Y., 1972.
 14. I. Hayashi, M. B. Panish and F. K. Reinhart, *J. Appl. Phys.*, **42**, 1929 (1971).
 15. H. C. Casey, Jr. and F. A. Trumbore, *Mater. Sci. Eng.*, **6**, 69 (1970).
 16. A. H. Bobeck and H. D. E. Scovil, *Scientific American*, June 1971, pp. 78-89.
 17. 1972 Wescon Technical Papers, Session 8, *Magnetic Bubbles*, Institute of Electrical and Electronic Engineers, San Francisco, Calif.

ADVANCED THERMO: Luks

Continued from page 183.

occurrence of a van der Waals "loop" in the region of coexistence is a manifestation of the approximate nature of the equation of state.⁷

Diffusional stability, or immiscibility phenomena, is presented in a manner abstracted from Prigogine and Defay.⁸ Margules solution models, starting with the "regular," are adequate to demonstrate a broad spectrum of possible immiscibility behavior. Prausnitz's discussion of the subject⁹ is a good complement to this topic.

6. Thermodynamics of Mixtures (2 weeks, or whatever time remains).

Obviously, two weeks is not enough to do any justice to the practical aspects of the thermodynamics of mixtures, such as the fugacity and activity concepts. Often, these few lectures are given in a qualitative way to provide an overview of what is presently relevant in chemical thermodynamics. This is generally all that the non-chemical engineers will desire while the chemical engineers have refuge in a second course for which this course is a prerequisite. The second course is a course in phase equilibria and uses Prausnitz⁹ as a text. It will not be discussed here.

In closing, it is satisfying to note that Equation (3.1-8)—(3.1-14) and Equation (3.4-9)—

(3.4-17) of Prausnitz,⁹ equations for the properties of mixtures with independent variables (P,T) and (V,T) relative to an ideal gas basis (T = T, P = 1 atm absolute), are derivable by students of the core course without recourse to the work of Beattie.¹⁰ □

REFERENCES

1. Holman, J. P., "Thermodynamics," McGraw-Hill, Inc. (1970); 2nd Edition (1974).
2. Reynolds, W. C., and H. C. Perkins, "Engineering Thermodynamics," McGraw-Hill, Inc. (1970).
3. Tisza, L., "Generalized Thermodynamics," M. I. T. Press (1970), ps. 5-38.
4. Callen, H. B., "Thermodynamics," John Wiley and Sons, Inc. (1960), ps. 3-130.
5. Denbigh, K., "The Principles of Chemical Equilibrium," 3rd Edition, Cambridge University Press (1971), See prob. 8, p. 213-214.
6. Zeleznik, F. J., and S. Gordon, I. & E. C. *60*(6), 27-57 (1968).
7. For example, see Appendix 9 of T. L. Hill's "Statistical Mechanics," McGraw-Hill, Inc. (1956), ps. 413-423.
8. Prigogine, I., and R. Defay, "Chemical Thermodynamics," Longmans (1954), ref. Chapters XV and XVI.
9. Prausnitz, J. M., "Molecular Thermodynamics of Fluid-Phase Equilibria," Prentice-Hall, Inc. (1969).
10. Beattie, J. A., *Chem. Rev.* **44**, 141-192 (1949).

MULTIVARIABLE CONTROL AND ESTIMATION: Edgar

Continued from page 171.

This latter approach is an interesting extension of classical single loop design.²⁰

SUMMARY

The course stresses those elements of modern control theory which appear to have the most promise of eventual applications and economic justification. The usefulness of the proposed techniques is tested via simulation and experimentation. A pilot plant distillation column has been chosen as a prototype system for testing multivariable strategies; focusing on a real system seems to enhance the students' interest. There is no question that use of a computer control laboratory strengthens the overall course, and hopefully the experience will motivate the students to use multivariable control and estimation to solve the difficult problems of process operation.

REFERENCES

1. Newell, R. B., Fisher, D. G., and Seborg, D. E., *AIChE J.*, 18, 976 (1972).
2. Smith, F. B., "Dynamic Modeling and Control of a Fluid Cat Cracker" 76th Natl. AIChE Meeting, Tulsa, OK, March, 1974.
3. Sage, A.P., "Optimum Systems Control," Prentice-Hall, Englewood Cliffs (1968).
4. Bryson, A. E., and Ho, Y. C., "Applied Optimal Control," Blaisdell, Waltham (1969).
5. Lapidus, L. and Luus, R., "Optimal Control of Engineering Processes, Blaisdell, Waltham (1967).
6. Koppel, L. B., "Introduction to Control Theory," Prentice-Hall, Englewood Cliffs (1968).
7. Ogata, K., "State Space Analysis of Control Systems," Prentice-Hall, Englewood Cliffs (1967).
8. Denn, M. M., "Optimization by Variational Methods," McGraw-Hill, New York, (1969).
9. Ellis, J. K., and White, G. W. T., *Control*, April-193, May-262, June-317 (1965).
10. Topaloglu, T., and Seborg, D. E., *Proc. JACC*, 309 (1974).
11. Jameson, A., *IEEE Trans. Auto. Cont.*, AC-15, 345 (1970).
12. Huckaba, C. E., Franke, F. R., May, F. P., Fairchild, B. T., and Distefano, G. P., *CEP Symp. Ser.*, 61, No. 55, 126 (1965).
13. O'Conner, G. E., and Denn, M. M., *Chem. Engr. Sci.*, 27, 121 (1972).
14. White, J. S., and Lee, H. Q., "User's Manual for VASP," NASA TM X-2417, Washington, D. C., October, 1971.
15. Hu, Y. C., and Ramirez, W. F., *AIChE J.*, 18, 479 (1972).
16. Edgar, T. F., Vermeychuk, J. G., and Lapidus, L., *Chem. Engr. Comm.*, 1, 57 (1973).
17. Schuldt, S. B., and Smith, F. B., *Proc. JACC*, 270 (1971).
18. Young, P. C., *Control Engr.*, October, 119, November, 118 (1969).
19. Hamilton, J. C., Seborg, D. E., and Fisher, D. G., *AIChE J.*, 19, 901 (1973).
20. MacFarlane, A. G. J., *Automatica*, 8, 455 (1972).

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A Course in

ENERGY ENGINEERING

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and J. T. SCHRODT
University of Kentucky
Lexington, Kentucky 40506

THE COURSE BEGAN BEFORE the students went home for the Christmas holidays. We asked them to find the cost of energy sources such as coal, heating oil, gasoline, natural gas, and electricity in their hometown. In addition to passing out the course outline and reading assignments, the first class period was spent tabulating the students' data. It was interesting to learn that two students from Kentucky came from homes heated by coal, and the cost of this coal was \$29 and \$31.50/ton. This was quite a jump from the 1971 national average of \$7.07/ton! A student volunteered to summarize the data on ditto masters along with the latest national averages and on the common basis of $\phi/10^6$ BTU.

Another assignment in this first part of the course was to find an energy forecast for U. S. consumption in 1985 or 2000. It was an eye-opener for all of us to see the difference in Inter Technology Corp.'s prediction of 99.3×10^{15} (a composite of 56 predictions) and Chase Manhattan Bank's 135×10^{15} BTU/year for 1985. The hazards of forecasts were further spelled out by the required reading of Doan's article (see references at end of article).

PRIOR ENERGY RESEARCH

KENTUCKY WITH VAST COAL reserves relies heavily on mining for a large fraction of its gross State product. In the interest of preserving these markets the University of Kentucky (UK) received State funding starting in 1972 for coal research. This money was to be used for economic and technical studies related to Kentucky coals.

Projects in the department of chemical engineering included such topics as high temperature sulfur removal from gases, certain aspects of high and low BTU gasification, sulfur removal from coal, and a study of the agglomerating character-

istics of coal. Thus in the Fall of 1972 four graduate students, three undergraduates and three post doctoral fellows were carrying out coal research under the direction of four faculty members. These numbers were augmented the following October when the department received an NSF-RANN grant in conjunction with the Ashland Oil Corporation. The focus of the research was liquefaction, and four separate projects in this area were initiated at that time.

During the summer of 1973 it became apparent that an increasing number of students and faculty would be involved in energy research. It was decided that two courses should be offered, one being an advanced undergraduate—M. S. level course, the other an M.S.—Ph.D. level course. The first was to be a complete survey of all types of energy and energy conversion processes. The second would be a course in fundamental chemical engineering principles applied to energy engineering.

COURSE OBJECTIVES

TO PROVIDE THE BROAD background needed to understand the nature of the problems we designed the first course as a series of lectures and class discussions that would accomplish the following:

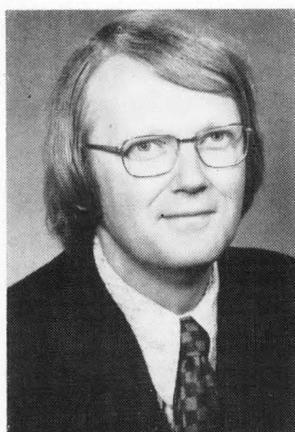
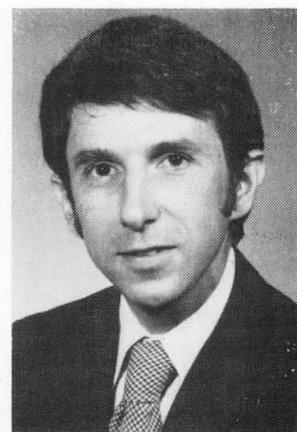
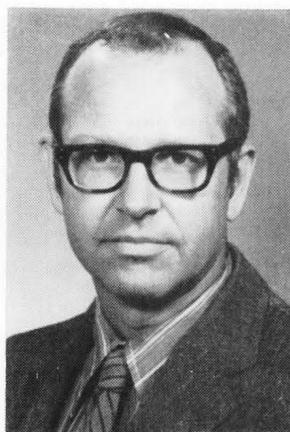
- Familiarize the learners with the scope of the energy problem.
- Refresh them with the basic engineering principles needed to ferret out those energy problems requiring engineering skills for solution from those that require other skills for solution.
- Provide the opportunity to review in a systematic fashion certain facets of interest, opportunity and promise in the energy area.
- Educate them to the energy based raw material needs of commerce and industry, particularly the CPI.
- Evaluate the short and long term potentials of established and novel energy conversion and conservation processes and practices.

In the short time in which we instigated this first course we foresaw that a consort of teaching faculty would be needed to handle both the broadness and depth of the course. Prerequisites were

Charles E. Hamrin, Jr. received his B.S., M.S., and Ph.D. degrees in Chemical Engineering from Northwestern University. He worked at the Y-12 Plant of Union Carbide for six years before joining the faculty of the University of Denver. He has been at the University of Kentucky since 1968 where his teaching has emphasized student involvement and discovery. (BELOW)

R. L. Kermode received his undergraduate education at Case Institute of Technology, and an M.S. and Ph.D. (1962) from Northwestern University. He has teaching experience at Carnegie-Mellon University and the University of Kentucky. His research interests are in the areas of process control and coal liquefaction. (LEFT PHOTO)

J. Thomas Schrodtt is an Associate Professor of Chemical Engineering at the University of Kentucky. He received the B.Ch.E. degree in 1960 and a Ph.D. in 1966 from the University of Louisville and a M.S. degree in 1962 from Villanova University. Dr. Schrodtt worked as a Senior Research Engineer for the Tennessee Eastman Company prior to joining the faculty at U.K. His teaching and research interests in fundamental thermodynamics and heat and mass transfer. (RIGHT PHOTO)



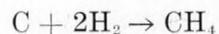
established for this faculty; each had to have a proficiency in the basic principles and each had to have an expertise in one or more of the elected areas of energy conversion or consumption. This required in several cases that faculty from other departments—Professors Cremers, Hahn, and Stewart from the ME Department—had to be called into the association. The prerequisites for students taking the course for credit amounted to an understanding of classical thermo, fluids and process principles or some equivalent thereof. Students from other disciplines desiring to audit the course were welcomed to sit in. The final class makeup consisted of 15 undergraduates, 14 Ch.E.'s and 1 Ag.E. and 16 Ch.E. graduate students.

COURSE CONTENT

THE COURSE CONTINUED as shown in the course outline. Thermodynamics was summarized in a handout of 20 important equations for energy conversion, conservation, entropy flow, and material transport. Sample problems were worked using a steam turbine to illustrate energy

balances and a chemical equilibrium problem with three simultaneous reactions occurring. Three homework problems covering a steam turbine, compressible fluid flow, and gasifier reaction equilibria were assigned and represented the quantitative portion of the course.

Flow sheets and gasifier design for low-BTU and pipeline quality gas, and for liquefaction, were presented during the next several weeks. Data from the Morgantown Gasifier of the USBM, for the first time using a caking coal (Kentucky No. 9), were presented to the class. The outlet gas composition was shown to compare favorably with a simple model of an adiabatic reactor in which the water-gas shift reaction was at equilibrium and methane was being produced by the reaction



Details of gas cleanup processes including liquid absorption, dry oxidation, and dry adsorption were also discussed. Current research at UK in this latter area was also detailed.

In addition to the text, *New Energy Technology* (by Hottel and Howard), a key reference to processes for producing pipeline quality gas was that of Bituminous Coal Research (see references). Gasification processes essentially consist of five major units: gasifier, water-gas shift reactor acid-gas removal system, methanator, and dryer. Discussion of the various AGA-OCR-USBM pilot-plant processes emphasized the unique features of each in terms of these five units. Liquefaction coverage was limited to the Sasol plant in South Africa and the H-Coal process.

In many instances novel learning techniques were used to draw the students into class participation. For example, the group process technique of role-playing was used to discuss solvent refining of coal. Five groups were formed with leaders being chosen based on highest first exam scores. In 1/2 hour, each group was asked to come

up with a process to remove sulfur from Western Kentucky coal (4% S, about half organic sulfur and half pyritic sulfur). A 2-minute presentation was to be made to the Governor and his aides trying to sell them on this process as part of his \$50 million energy package. (This bill was eventually signed in the Chemical Engineering Department's Unit Operations Laboratory.) Having received the assignment, one group left the room, and we wondered if they would return. The groups in the room became actively engaged in discussion, and those students doing coal research projects were particularly vocal. It was the first time for many to verbalize their ideas of coal processing based on class lectures and outside reading. No new processes evolved but a valuable learning experience occurred.

The remaining course topics were covered in one or two sessions except for nuclear which was presented in three lectures. Professor Bill Conger of our department covered the hydrogen economy concept based on his research in collaboration with Dean Funk.

Two special classes were those led by distinguished visitors to the Engineering College. Professor Jimmy Wen, Chairman of the Dept. of Chemical Engineering at West Virginia, gave an excellent overview of the short and long term solutions to the U. S. energy problem. Near the end of the semester, Professor Jack Howard, co-

author of the text, gave an extemporaneous talk on tar sands and oil shale which supplemented the heavy emphasis on coal during most of the course.

Table 1

ENERGY ENGINEERING COURSE OUTLINE

- I. Energy Consumption, Demand, Transportation, Storage, and Costs (CEH)
- II. Thermodynamic Laws Governing Conservation and Availability of Energy (JTS)
- III. Fossil Fuel to Fuel Conversion
 - A. Low-Btu Gas (JTS)
 - B. Pipeline Quality Gas (RIK)
 - C. Synthetic Crude Oil (RIK)
 - D. Solvent Refined Coal (CEH)
- IV. Dependence of Industry on Hydrocarbon Feedstocks
 - A. Petrochemical (JTS)
 - B. Steel, Glass, Fertilizer, etc. (RIK)
- V. Electrical Power Generation
 - A. Non-Nuclear (OWS)
 - B. Nuclear (OJH)
- VI. Other Energy Sources
 - A. Geothermal (JTS)
 - B. Magnetohydrodynamics (CJC)
 - C. Solar (CEH)
 - D. Fuel Cells (RIK)
 - E. Hydrogen economy (WLC)

CACHE
COMPUTER
PROBLEMS



CHEMICAL ENGINEERING EDUCATION, in cooperation with the CACHE (Computer Aides to Chemical Engineering) Committee, is initiating the publication of proven computer-based homework problems as a regular feature of this journal.

Problems submitted for publication should be documented according to the published "Standards for CACHE Computer Programs" (September 1971). That document is available now through the CACHE representative in your department or from the CACHE Computer Problems Editor. Because of space limitations, problems should normally be limited to twelve pages total; either typed double-spaced or actual computer listings. A problem exceeding this limit will be considered. For such a problem the article will have to be extracted from the complete problem description. The procedure to distribute the total documentation may involve distribution at the cost of reproduction by the author.

Before a problem is accepted for publication it will pass through the following review steps:

- 1) Selection from among all the contributions an interesting problem by the CACHE Computer Problem Advisory Board
- 2) Documentation review (with revisions if necessary) to guarantee adherence to the "Standards for CACHE Computer Programs"
- 3) Program testing by running it on a minimum of three different computer systems.

Problems should be submitted to:

Dr. Gary Powers
Carnegie-Mellon University
Pittsburgh, Penn. 15213

DIGITAL CONTROL: Corripio Continued from page 163.

veloped under the project THEMIS research grant at LSU. Formulas for all of these methods have been programmed as a subroutine that computes the parameters of the control algorithm given the modes, the sampling interval and the parameters of a first-order plus dead-time (transportation lag or time delay) model of the process. The students use this subroutine, also the subject of a former term project in this course, to observe the responses produced by the different formulas on systems simulated on the hybrid computer.

The justification of digital control computers is usually based on the ease and economy of implementing control techniques more sophisticated than simple feedback. The advanced techniques of feedforward control, cascade control, elimination of loop interaction through decoupling, on-line identification for adaptive control of nonlinear processes, and dead-time compensation are covered from the point of view of digital versus analog implementation. Term projects in these areas are assigned to individual students. Although use of

the hybrid computer is encouraged with views to the development of demonstration problems, the students do not always comply.

The optimization of steady-state process operation was the first type of computer control applications and is still one of the most popular. 20—CHEM. ENGINEERING — 12281 — Jerry Although the subject of optimization is covered in detail in another graduate course, an overview of the problem is presented from the point of view of on-line application to processes.

The text used in this course is "Digital Computer Process Control," published by Intext (1972) and authored by Dr. Cecil L. Smith, Chairman of the Department of Computer Science at LSU and originator of the course. In addition, a collection of articles covering specific topics is used as reference material.

In summary, this course offers fairly complete coverage of the subject of digital computer control of chemical processes, plus a working control of chemical processes, plus a working experience through the use of hybrid simulation of digital control loops. Since the subject matter is in a state of rapid development, the course itself is in a state of evolution. The students contribute to this evolution through their term projects and through constructive criticism of the subject matter and methods of presentation. □



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THE DEVELOPMENT OF MASS TRANSFER THEORY

THOMAS K. SHERWOOD

University of California

Berkeley, Calif. 94720

Mass transfer has always been a central theme in chemical engineering. We have developed a special competence in the design of separation processes from batch distillation to diffusion plants for enriching uranium—235—and have had little competition from other branches in this area. Perhaps chemical engineering would not have been developed as it has if mechanical engineers had studied physical chemistry.

The basic tools available to the engineer in the design of a separation scheme are three: the laws of conservation of mass, energy, and the elements; data and theory pertaining to phase equilibria; and knowledge of rates of transport from one phase to another. The usual plan is to accomplish a preferential enrichment of a desired species in a second phase, followed by inexpensive mechanical separation of the gases, liquids, or solids. It is my intention to talk about the third tool of the design engineer—knowledge of mass transfer between phases—with a critical review of the research over the years which has led to the present state of this art.

This is not only the twentieth anniversary of the department at Houston but the fiftieth anniversary of the publication of "Principles of Chemical Engineering" by Walker, Lewis, and McAdams in 1923. That book was a milestone, for it established chemical engineering as a separate and unique branch of engineering, and stimulated the proliferation of chemical engineering departments in many universities. Its focus on the quantitative treatment of the unit operations was challenging and exciting, and the "unit operations" concept served the profession well for some twenty years.

The name "chemical engineering" had been coined by Davis in England some fifty years earlier, and there was at least one curriculum

labeled "chemical engineering" by 1888. The early four-year curricula generally consisted of two years of mechanical engineering and two years of chemistry. By 1923 the new approach had much to start with. Physical chemistry was well developed; multiple effect evaporation and rectification had been invented in Europe; and the ideas of reflux and countercurrent staging had been recognized and analyzed.

The concept of staged operations appears to be unique to chemical engineering. Several years ago a well-known mechanical engineer told me that he had visited Oak Ridge and had been astounded by the plant's capacity to produce uranium 235. I told him that I had understood the productive capacity to be an extremely well-guarded secret, and asked how he had learned what it was. He answered that it was simple—he had seen the sizes and estimated the r. p. m. of the circulating gas compressors. I asked him if he had ever heard of reflux. His reply was "No, what is reflux?"

There were not many chemical engineers in the twenties and early thirties, but much was accomplished in the development of the unit operations. McCabe and Thiele, working within a few feet of each other at M. I. T., independently conceived their graphical representation of Sorel's algebraic analysis of binary rectification. The now-familiar friction factor graph was imported from England and publicized in this country by chemical engineers. The simpler staged operations were analyzed, and the McCabe-Thiele diagram adapted for gas absorption, solvent extraction, and leaching. The humidity chart had been invented by Grosvenor in 1908 and was published

Professor Sherwood's paper is reproduced by permission of the copyright owner, and was taken from: Proceedings of the 20th Anniversary Symposium on "Mass Transfer and Diffusion," of the Department of Chemical Engineering, University of Houston, held April 5-6, 1973. Other lectures presented at the Symposium were: "Tomorrow's Challenges," by H. L. Toor; "Today's Problems and Some Approaches to Their Solution," by P. V. Danckwerts; "Industry Problems in Mass Transfer and Diffusion," by J. R. Fair. In addition the lecturers participated in a panel discussion on "Developments—Past and Present." Copies of the Symposium are available at a cost of \$5.00 by writing to: Herbert Kent, Executive Officer, ChE Dept. of Houston, Houston, Texas 77004.

in Volume 1 of the Transactions of the American Institute of Chemical Engineers, greatly simplifying analyses of drying and air conditioning.

EARLY PERIOD

IN THIS PERIOD OF some twenty years prior to World War II the emphasis was on the collection and correlation of data intended to be of direct use by the practicing design engineer. Industry had few such data and published little, so schools felt a responsibility to fill the need. This urge to be immediately helpful to industry has largely disappeared today; research in schools is now along more scientific and theoretical lines, hopefully of value to industry a generation hence. Our rapport with industry has suffered.

Research on mass transfer between phases was strong in the twenties and thirties, even as it is today. Then, as now, the research was mostly by academics. The film model had been invented by Nernst in 1904, and by others around the turn of the century. This was elaborated by Whitman and Lewis [20, 37] through the concept of additivity of resistances of two phases in contact. Murphree [22] defined a useful plate or stage efficiency, which was shown to be related to rate coefficients. The main variables affecting plate efficiency—contactor design, fluid properties and the nature of the phase equilibria—were elucidated in numerous thesis investigations by graduate students. But the most remarkable thing about this period was the obsession with studies of packed towers. Most of the experimental work was carried out in 2- and 3-in. columns, much too small to provide useful design data for the industrial process engineer. Data were obtained on flooding, holdup, and pressure drop as well as mass transfer rates, and correlations based on dimensionless groups were developed, without much reference to any valid theory. The profession seemed to have a one-track mind, and the AIChE was referred to as “Packed Tower Institute.” Important as packed towers were, and continue to be, it appeared that academic investigators had lost their sense of perspective, neglecting other problems of similar relevance and importance.

Let me turn now to a review of the developments of the theory of mass transfer processes, with a few critical comments as to which of these seem now to be of importance, and which do not. Even in the twenties we were in moderate-

ly good shape as to how to deal with diffusion within a single phase. Physical chemists had provided us with an understanding of diffusion in gases, and by 1934 we had semi-empirical correlations of diffusion coefficients in binary gas systems. The classical kinetic theory has since been developed to allow for interactions between unlike molecules, and the modern kinetic theory is adequate for most engineering purposes. There still is no adequate theory of the liquid state, however, and we must rely on inadequate empirical correlations of diffusion coefficients in liquids. Chemical engineers have been major contributors to the development of the useful correlations now available.

THE MAIN THRUST of the theoretical studies has been quite logically on mass transfer between phases, since the understanding of the factors which determine the rate of transfer is the basic objective.

If the flow past the interface is laminar, analysis is often possible by combining the transport relations with equations describing the flow field. This has been done successfully for laminar flow in tubes, rotating disks, falling liquid films on inclined or vertical surfaces, over spheres, and creeping flow around spheres. The theoretical analyses for such cases are sometimes better than the experimental data.

Perhaps ChE is emerging from an era of empiricism... we have much concern with complex physical phenomena, and we have not yet arrived at the point where all can be left to the computer.

In industrial practice, however, the flow past the mass-transfer interface is usually turbulent, and attempts at theoretical analysis have been frustrated by the lack of an adequate understanding of turbulence—especially of turbulence near a phase boundary. What progress has been made is due as much to chemical engineers as to specialists in fluid mechanics. The early approach was to develop empirical correlations relating dimensionless groups, such as the mass-transfer Nusselt number, and the Reynold and Schmidt numbers. This was hardly a theoretical approach in any real sense, but has served a useful purpose over a period of many years.

One theoretical approach which has fascinated so many workers is the development of the so-called "analogies" between mass, momentum, and heat transfer. If these could be successful, they would provide a way to use the accumulated body of knowledge regarding turbulent flow of fluids for the prediction of mass and heat transfer coefficients. The first of these was the Reynolds analogy, which stated that the Stanton number for heat transfer should be equal to one-half the Fanning friction factor. This came close to fitting experimental data on heat transfer in tubes with gases in turbulent flow, but not for water or oils. It made no allowance for the different molecular properties of the fluids.

Attempts to clarify the situation focussed on transfer from a turbulent fluid to a solid surface, as in the case of fully-developed turbulent flow in a round tube. Consideration of transfer between two fluids, as from gas to liquid, or between two immiscible liquids, came later. It was well established that in pipe flow there is no slip at the wall, so it seemed logical that turbulent mixing could play no part in the transport mechanism as the distance from the wall approached the mathematical limit of zero. In this limit the mass transfer flux should be proportional to the flux power of the molecular diffusion coefficient, D . The main turbulent stream is so well mixed that solute is transported radially at fluxes much greater than can possibly be explained by molecular diffusion. In the two limits of the wall and the main flow the radial flux is proportional to D^1 and D^0 , respectively. It is not surprising that most of our mass transfer correlations show the mass transfer coefficient to be proportional to D^n , where n is between zero and unity.

The spectrum of motion from eddies to molecules is suggested by this little verse—authorship unknown:

Big size whirls have little whirls
That feed on their velocity

And little whirls have lesser whirls
And so on to viscosity.

It seems logical to assume that molecular and eddy diffusion take place in parallel, and that the flux toward the wall can be expressed by a version of Fick's law in which the "total diffusivity" is the sum of the molecular diffusion coefficient, D , and the eddy diffusion coefficient, E . The first is a property of a binary mixture, but the eddy coefficient E depends on the nature of the flow and the distance from the wall.

By the late twenties the early "stagnant film" model was realized to be a gross oversimplification. Whitman, who is often mistakenly quoted as having applied it rigorously, noted in 1922 that a sharp boundary was assumed between the stagnant film and the turbulent core, but that "actually no such sharp demarcation exists." Whitman and Lewis did not advocate the film model; their papers developed a way to add the resistances of two fluid phases in contact.

ANALOGIES

SINCE MASS TRANSFER at a phase boundary depends on the varying eddy diffusivity it is evident that any theory of the overall process will necessarily require a theory of the variation of E with the flow conditions and the distance from the wall. The first attempt to allow for the large variation of E with distance in the vicinity of the wall was made in 1932 by a well-known chemical engineer, the late E. V. Murphree [22]. Murphree assumed the total diffusivity to vary as the cube of the distance from the wall, y , up to some limit y_1 , beyond which the parabolic velocity deficiency law determined the nature of the flow in the bulk or turbulent core. This semi-empirical approach correlated data on heat transfer in pipes over a limited range of Prandtl numbers, which the Reynolds analogy had failed to do.

1939 saw the publication of Von Karman's elegant analysis [34] of the possibilities of developing a unified theory of mass, heat, and mo-

Professor Sherwood joined the Berkeley faculty in 1970, after spending most of his professional life at M.I.T. After five years with the O.S.R.D. during the war, he was Dean of Engineering at M.I.T. from 1948-1954. Many of his publications have dealt with various aspects of mass transfer, and "Mass Transfer" is the title of a new book now in press, written jointly with R. L. Pigford and C. R. Wilke. He is the recipient of the Walker, Founder's, and Lewis awards of the AIChE, the Murphree award of the A.C.S., and the Presidential Medal for Merit.

momentum transport from a turbulent stream to a solid wall; this had been a fascinating idea since Reynolds' time. Eddies appear to transport mass, heat, or momentum by similar if not identical processes, so it seemed logical that E could be equated, or related to, the eddy viscosity. The similarity of the three processes is suggested by comparing the Reynolds modification of the Navier-Stokes equations for turbulent flow in the x -direction:

Momentum:

$$\bar{U}_x \frac{\partial \bar{U}_x}{\partial x} + \bar{U}_y \frac{\partial \bar{U}_x}{\partial y} + \bar{U}_z \frac{\partial \bar{U}_x}{\partial z} = \frac{1}{\rho} \left[\frac{\partial}{\partial x} \left(\mu \frac{\partial \bar{U}_x}{\partial x} - \rho \bar{u}_x \bar{u}_x \right) + \frac{\partial}{\partial y} \left(\mu \frac{\partial \bar{U}_x}{\partial y} - \rho \bar{u}_x \bar{u}_y \right) + \frac{\partial}{\partial z} \left(\mu \frac{\partial \bar{U}_x}{\partial z} - \rho \bar{u}_x \bar{u}_z \right) \right] - \frac{g_c}{\rho} \frac{\partial \bar{P}}{\partial x} \quad (1)$$

Heat:

$$\bar{U}_x \frac{\partial \bar{T}}{\partial x} + \bar{U}_y \frac{\partial \bar{T}}{\partial y} + \bar{U}_z \frac{\partial \bar{T}}{\partial z} = \frac{1}{\rho C_p} \left[\frac{\partial}{\partial x} \left(k \frac{\partial \bar{T}}{\partial x} - \rho C_p \bar{u}_x \bar{t} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial \bar{T}}{\partial y} - \rho C_p \bar{u}_y \bar{t} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial \bar{T}}{\partial z} - \rho C_p \bar{u}_z \bar{t} \right) \right] \quad (2)$$

Mass:

$$\bar{U}_x \frac{\partial \bar{Y}_A}{\partial x} + \bar{U}_y \frac{\partial \bar{Y}_A}{\partial y} + \bar{U}_z \frac{\partial \bar{Y}_A}{\partial z} = \frac{\partial}{\partial x} \left(D \frac{\partial \bar{Y}_A}{\partial x} - \bar{u}_x \bar{Y}_A' \right) + \frac{\partial}{\partial y} \left(D \frac{\partial \bar{Y}_A}{\partial y} - \bar{u}_y \bar{Y}_A' \right) + \frac{\partial}{\partial z} \left(D \frac{\partial \bar{Y}_A}{\partial z} - \bar{u}_z \bar{Y}_A' \right) \quad (3)$$

It is noted that the similarity is not complete: momentum is a vector but temperature and mole fractions are scalars. The first equation has an extra term involving pressure gradient. Furthermore, as Beddingfield and Drew [1] have shown, the equation for mass transfer is valid as written only for low concentrations of the species being transferred if diffusion velocities are to be related to a plane of no net molal transport in order to gain the advantage that D in binary gas systems is then independent of concentration.

A remarkable general correlation of velocity profiles for turbulent flow in pipes had been developed by workers in fluid mechanics, from which the eddy viscosity could be obtained. Velocity profiles for both gases and liquids over a wide range of Reynolds numbers were represented by a single curve of u^+ vs. y^+ , where u^+ is a dimensionless local velocity, and y^+ the dimensionless distance from the wall. The eddy viscosity is obtained from the slope of this curve. Von Karman wrote simple equations for three segments of the $u^+ \sim y^+$ function, and differentiated these to obtain the eddy viscosity as a function of y^+ . He then assumed the eddy diffusion coefficient to be equal to the eddy viscosity, and integrated the heat flux equation from wall to

bulk fluid. The result was an equation relating the Stanton number for heat transfer to the friction factor and the Prandtl number, which agreed quite well with data on heat transfer data for gases and various liquids. The corresponding equation for mass transfer is easily obtained and has the same form.

Von Karman's publication precipitated a minor avalanche of variations of the analogy idea, and these are still coming out (33, 35, 36). Von Karman's analysis can be understood by noting the basic equations employed, here written for mass transfer:

$$\tau g_c = -(\nu + E_v) \frac{d(\bar{U}\rho)}{dy} = \frac{1}{2} f \rho \bar{U}_{Av}^2 \frac{r}{r_w} \quad (4)$$

$$u^+ = f(y^+) \quad (5)$$

$$u^+ \equiv \frac{\bar{U}}{\bar{U}_{Av}} \sqrt{\frac{2}{f}}; \quad y^+ \equiv \frac{(r_o - r) \bar{U}_{Av}}{\nu} \sqrt{\frac{f}{2}}$$

$$E_v/\nu = \frac{r}{r_w} \frac{dy^+}{du^+} - 1 \cong E_D/\nu \quad (6)$$

$$J_A = k_c (C_{Av} - C_w) = -(D + E_D) \frac{dc}{dy} \quad (7)$$

$$\frac{1}{St} = \frac{\bar{U}_{Av}}{k_c} = \frac{2}{f} + \sqrt{\frac{2}{f}} f(Sc) \quad (8)$$

The function of the Schmidt number stems from the assumed relation between u^+ and y^+ ; the variation of St with the Reynolds number appears in the friction factor.

Various simplifying assumptions are involved in arriving at the last equation by the derivation outlined. Most of these are reasonable, though it is now known that E_D and E_v may differ substantially. In fact Von Karman's analysis, and later modifications of it, represent heat transfer data for turbulent flow in pipes quite well. Most of the heat transfer data involved Prandtl numbers in the range of about 0.5 to 35. The theory failed, however for heat transfer to liquid metals, which have very small Prandtl numbers. Of more importance in chemical engineering, the analysis failed seriously for high Schmidt numbers. In the liquid systems of interest to chemical engineers the Schmidt numbers range from several hundred to several thousand. Much re-

search has been directed towards improving this situation by modifying the analogy approach.

In liquid systems with high Schmidt numbers the concentration boundary layer is exceedingly thin, that is, almost all of the concentration drop occurs within a few microns of the wall, generally at y^+ from zero to perhaps 2. There are essentially no data on the velocity profiles in this region; it is too close to the wall for measurements by Pitot tubes. Furthermore, since in this region u^+ and y^+ are very nearly equal, the precision in getting E_v by Eq. 6 is very poor. It appears now that it may be some years before we have a quantitative understanding of this region very near the wall; current research using optical techniques indicates that the flow patterns there are quite complicated.

In this dilemma, numerous analysts have simply assumed the needed function. Anyone can develop a new "analogy" by doing this. It doesn't matter whether one assumes a new $u^+ \sim y^+$ relation, or E_v as a function of y^+ , or, more directly, E_p , as a function of y or y^+ . By trial and error one can find a basic function which will lead to an integrated final equation fitting the data over a wide range of Prandtl and Schmidt numbers.

IT SEEMS TO ME that there have been more "analogies" developed in this way than we have any need for. Most involve too much of an aspect of assuming the answer to be called theoretical accomplishments. What we seem to need is new and better techniques for studying the wall region. Nedderman [23] and Fowles [29] have employed optical methods to record direction and speed of particles flowing very near the wall. Interferometric and laser techniques may work, and Kline's photographs [18] of dye streaks and tiny bubbles are fascinating. Already the idea of a laminar sublayer has been made obsolete—by observation, not by theory.

Now let me go back to 1934 and comment on the remarkably simple and useful Chilton-Colburn analogy, which may be expressed in the form

$$\frac{k_c}{U_{Av}} Sc^{2/3} = \frac{h}{C_p \rho U_{Av}} Pr^{2/3} = \frac{f}{2} \quad (9)$$

I suspect that this was based on (a) the observation that the simple Reynolds analogy held for heat transfer when Pr was near unity, (b) the fact that $Pr^{2/3}$ had been shown theoretically to

apply to transport through a laminar boundary layer, (c) the apparent validity of the simple empirical function $1.0 Pr^{2/3}$ to represent heat transfer data over a limited range of Pr , and (d) an intuitive guess that because of the similarity of the mechanisms of heat and mass transfer k_c

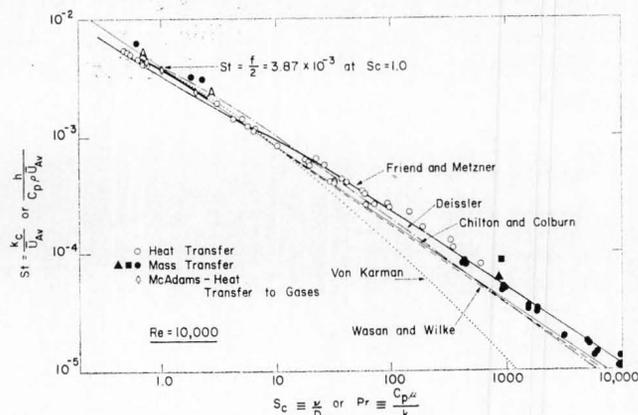


FIG. 1 Plot of Sc vs Pr for $Re=10,000$.

should vary with Sc in the same way that h does with Pr . In any case it has been found to agree surprisingly well with a large amount of subsequent data. The first equality seems to be general for turbulent flow; and second when there is only "skin friction" with no form drag. It is interesting that the proper choice of constants in Murphree's analysis will make it agree with Chilton and Colburn [5].

Let me summarize this review of the analogies by showing how several of them compare with data on heat and mass transfer for fully developed turbulent flow in a tube. Figure 1 is a graph of St vs. Sc or Pr for $Re=10,000$, with lines representing five of the better-known analogies. The open circles represent data on heat transfer to gases, water, oils, molten salt, organic liquids, and aqueous solutions of sugars. These were collected from the extensive literature by Friend and Metzner [11]. The solid points at large Sc represent the excellent data of Myerink and Friedlander [21] and of Harriott and Hamilton [14] on the dissolution of tubes of slightly soluble solid organic acids. The solid points at $0.6 < Sc < 2.5$ are Gilliland's data [12] for vaporization of liquids into air in a wetted-wall column. McAdam's correlation for heat transfer to gasses is shown as line A-A.

At $Sc=1$, all of the lines shown pass near $St = \frac{1}{2}f = 3.87 \times 10^{-3}$, which the Reynolds analogy requires. Friend and Metzner's line passes through the data points, as is perhaps to be ex-

pected, since their analogy is based on the data points represented by the open circles. The recent analogy developed by Notter and Sleicher [24], based on carefully selected heat transfer data, agrees closely with Friend and Metzner. The Von Karman line, based on the general correlation of velocity profiles, does poorly. This is because Von Karman took the eddy diffusivity to be zero from the wall to $y^+ = 5$; it is now clear that a very small amount of eddy diffusion at low values of y^+ can be quite important at large Sc . The most remarkable thing about this comparison is the fact that the Chilton-Colburn analogy does as well as it does; their equation was proposed at a time when there were no data on heat transfer above a Pr of about 20, and no data on mass transfer at Sc greater than 2.6. It is also notable that this graph represents an enormous range of flow conditions and of physical properties of the fluids.

I have discussed these analogies at some length because they constitute a major effort to develop a theory of mass transfer between phases in the important turbulent regime. There are also the "models," of which the first was the "stagnant film" model. It implies that the transport rate should be proportional to the first power of the molecular diffusion coefficient, which is not true, but it can still be successfully employed for a variety of purposes. It gives reliable predictions of the ratio of the mass transfer flux with simultaneous chemical reaction to that attained without chemical reaction under similar conditions. It does equally well in predicting the effect of convective fluxes in the direction of diffusion on the rates of mass or heat transfer.

INTERPHASE MASS TRANSFER

NUMEROUS MODELS OF the conditions at a phase boundary have been proposed to provide a basis for a theory of interphase mass transfer. The three best known are the stagnant film model, the penetration theory, and the turbulent boundary layer model. The allowance for the variation of eddy diffusivity with distance from the wall, as in the analogies, is the basis of the turbulent boundary layer model.

The penetration model pictures small fluid elements contacting the phase boundary for brief periods during which transient diffusion occurs, and then being replaced by fresh fluid from the bulk. This was suggested by Higbie in 1935 [16]

as applicable to bubbles moving in a liquid, and to gas-liquid contacting in packed towers, where freshly mixed liquid is supplied to successive packing elements. It led to the conclusion that the transport flux should be proportional to the square root of the molecular diffusion coefficient. This has been found to be approximately true in a wide variety of flow systems, including the absorption of sparingly soluble gases in packed towers.

An important extension of the penetration theory was proposed by Professor Danckwerts in 1951 [7]. Whereas Higbie had taken the exposure time to be the same for all of the repeated contacts of the fluid with the interface, Danckwerts employed a wide spectrum of contact times and averaged the varying degrees of penetration. Like the Higbie model, this concept leads to the conclusion that the transport flux should be proportional to the square root of D . It is not generally believed that fluid eddies reach a fixed interface, such as the wall of a tube, but there is increasing evidence that this may be so. The model makes particularly good sense when applied to conditions at the interface between a gas and a stirred liquid. Watching the surface of a swift but deep river, or of a well-stirred liquid in a laboratory vessel, it is not hard to discern fluid elements which come up from below and then appear to move back down after brief periods of contact with the air at the surface.

As applied in the simplest cases, these four models lead to the following equations for the mass transfer coefficient k_c :

$$\text{Film: } k_c = \frac{D}{y_0} \quad (10)$$

$$\text{Penetration: } k_c = 2\sqrt{\frac{D}{\pi t}} \quad (11)$$

$$\text{Surface-Renewal: } k_c = \sqrt{Ds} \quad (12)$$

Turbulent Boundary Layer:

$$k_c = \frac{U_{Av}}{\frac{2}{f} + \sqrt{\frac{2}{f}} f(Sc)} \quad (13)$$

The first three, to be useful, require knowledge of the effective film thickness, y_0 , the contact

time, t , or the fractional rate of surface renewal, s . The last requires that $f_2(Sc)$ be specified, which could be done if the variation of eddy diffusivity through the boundary layer were known. Little is known about y_0 , t , s , or $f_2(Sc)$, so as theories all four models are incomplete.

It is interesting that the models described perhaps owe their origin to Osborne Reynolds [27] who wrote in 1874 that the heat flux to a wall "is proportional to the internal diffusion of the fluid at and near the surface," and states that the heat flux depends on two things: "1. the natural internal diffusion of the fluid when at rest, and 2. the eddies caused by the visible motion which mixes the fluid up and continually brings fresh particles into contact with the surface. The first of these causes is independent of the velocity of the fluid. . . The second cause, the effect of the eddies, arises entirely from the motion of the fluid. . ."

SIMULTANEOUS CHEMICAL REACTION

IT IS NOT POSSIBLE for me to cover much of the development of the various theories used in practice by chemical engineers, even in the restricted area of mass transfer, but let me comment on two other important theoretical developments. The first is mass transfer with simultaneous chemical reaction, the subject of numerous papers in our journals. This started in 1929 by Hatta [15], who employed the film model to develop a theory of gas absorption followed by reaction in the liquid, as in the absorption of CO_2 by alkaline solutions. Following Hatta there has been a proliferation of theoretical analyses of all kinds of cases thought to be of practical importance, and useful generalizations, notably by Hoftzyer and Van Krevelen [17] and by Brian [3, 4]. Hatta's use of the film model was suspect, but Danckwerts and Kennedy [8] have shown that the penetration model gives essentially the same results in many instances.

These theories do not predict rates of mass transfer, but generally lead to equations expressing the enhancement of the rate by the simultaneous reaction, that is, the ratio of the rate with chemical reaction to that for physical absorption. Professor Danckwerts' recent book [9] summarizes the whole subject, with special reference to the absorption of acid gases by alkaline solutions, so important in the manufacture of hydrogen and of synthetic natural gas.

It might seem that some of the cases analyzed

will never find practical application, but one cannot predict. When I recently had occasion to analyze the process of SO_2 absorption by a suspension of limestone particles in a stack gas scrubber I was surprised and pleased to find this

It is not generally believed that fluid eddies reach a fixed interface, such as the wall of a tube, but there is increasing evidence that this may be so.

case analyzed in a published paper (26). However, it may be that we are running into the law of diminishing returns in pursuing these analyses, and that more experimental studies are in order. There is nothing like a surprising new fact to stimulate the development of better concepts and theories.

Another area in which we have made great progress is that of diffusion and reaction in porous catalysts. This subject is of great practical importance because of the enormous success of catalytic processes in the chemical and petroleum industries. The pioneering papers of the U. S. chemical engineer Thiele [32], and the Russian Zeldowitsch [38] in 1939, started a flurry of experimental and theoretical studies. We have now learned a lot about bulk and Knudsen diffusion in pores of simple geometry, and are beginning to tackle the much more difficult problem of surface diffusion. All kinds of cases have been analyzed, assuming both power-law and Langmuir-Hinshelwood kinetics, heat effects, and various geometries of the catalyst particle. The decrease in the effectiveness factor with increase in particle size is understood at least qualitatively, although I find highly successful catalyst research people in industry who use the theory so little that they think a low effectiveness factor indicates a relatively inactive catalyst.

Apart from the present mystery regarding surface diffusion, the stumbling blocks to better development of the theory would appear to be inadequate understanding of the mechanism of surface catalysis, and the difficulty of describing the complex structure of a porous solid by one or two numbers.

Many industrial processes involve the absorption of reacting gases by a liquid containing suspended particles of a catalyst. This operation was described quantitatively in 1932 by three chemists [6], who showed the merit of plotting the recipro-

cal of the rate vs. the reciprocal of the catalyst loading in the slurry. The intercept, corresponding to infinite catalyst loading, is a measure of the mass transfer resistance to the absorption of the gas. The situation has been generally understood by chemical engineers for 40 years, but there are still some chemists who attempt to analyze such processes by power-law or other kinetics when the controlling factor is actually the rate of gas absorption.

THE MARANGONI EFFECT

FINALLY, LET ME COMMENT briefly on the phenomenon of interfacial turbulence, or the Marangoni effect. Spontaneous emulsification of two liquids has been known for many years, but the important role of interfacial turbulence on mass transfer at an interface was brought forcibly to the attention of chemical engineers by Lewis and Pratt in 1953 [19], and by Jim Wei [28] in the course of his doctorate research in 1957. As mass transfer takes place, the solute concentration, and consequently, the interfacial tension vary from spot to spot over the surface. This causes spreading and contraction of the surface elements, which "is so rapid that the momentum of the spreading liquid is sufficient to break the center of the point source and expose subjacent liquid drawn from below the surface (10)." The result is surface renewal, usually with development of ripples, and an increase in the rate of mass transfer. The effect depends on the direction of the mass transfer flux, and the phenomenon obviously introduces new and difficult problems in attempts at theoretical analyses of mass transfer between two fluid phases.

Research directed to an understanding of the role of interfacial turbulence on mass transfer has proliferated in the last twenty years. This is proper, since the effect can be quite large, and requires major adjustment of the simple two-film picture. Excellent pictures of the phenomenon have been published by Dr. H. Sawistowski of Imperial College, London, and by others. The first important theoretical attacks appear to be those of Pearson [25] and of Sternling and Scriven [30]; Brian's recent introduction of the Gibbs layer adsorption extends the theory and is evidently a major contribution [2]. But the theory of this phenomenon, of real practical importance, is still in its infancy. Its development to the point of practical application in design presents a challenge to chemical engineers inclined towards

theoretical studies. Do not tackle it without a thorough background in physical and colloid chemistry.

Chemical engineers can be proud of the development of the profession since Walker, Lewis, and McAdams in 1923. The chemical and petroleum industries have prospered, with the help of U.S.-trained chemical engineers. Plants have been built and operated successfully, usually at a profit. But our contributions to the theory of mass transfer between phases have not been remarkable, at least within the definition of a theory as being valid for quantitative *a priori* predictions useful in design. A major difficulty is that we desire theories applicable in turbulent flow, and not much basically new has been learned about turbulence in the last 40 years.

However, chemical engineers have developed a unique skill in using the *form* of a theory. A modest theory is better than no theory at all. Even the simple equation $q = UA\Delta t$ for heat transfer enables us to eliminate two variables and concentrate our attention on the manner in which the heat transfer coefficient varies with the geometry and the fluid flow. There are many examples of this. The Van Laar equations for binary vapor-liquid equilibria were rejected by scientists because the theory did not work in the prediction of the constants. But chemical engineers found the *form* of the theory to be remarkably good—two data points are enough to provide

It may be that we are running into the law of diminishing returns . . . and that more experimental studies are in order. There is nothing like a surprising new fact to stimulate the development of better concepts and theories.

the Van Laar constants, and make it possible to predict complete y-x diagrams for complex binaries, including azeotropes.

Similarly, the models of the mechanism of mass transfer between phases provide the form if not the substance of a theory, and make it possible to develop correlations of experimental data on a rational and useful basis.

It is too much to expect that in fifty years we would have developed a fundamental and quantitative theory which would enable us to predict rates of mass transfer in turbulent flow. That is a goal for the future, probably requiring more

progress in understanding turbulence. Such a theory would be a feat comparable to the development of the kinetic theory of gases, and these are not frequent.

THEORETICAL ACCOMPLISHMENTS

THERE HAVE, OF COURSE, been a number of theoretical accomplishments about which chemical engineers can be proud. The wet-bulb thermometer is a fascinating example. This device was not understood until about 100 years ago, when Maxwell, using what amounted to our film theory, explained the dynamic equilibrium established when the rate of heat transfer from air to wet wick just equalled the latent heat of vaporization of the water evaporating at the wet-bulb temperature. About 1910 it was noticed by Willis Carrier that the wet-bulb temperature coincided with the calculated temperature of adiabatic saturation. Why should this be? It was some years later that W. K. Lewis and J. H. Arnold explained this. The ratio of the heat transfer coefficient, air to wet-bulb, to the mass transfer coefficient determining vaporization, depends on the molecular properties of air and water, and these just happen to have values such that the equations for the wet-bulb depression and for adiabatic saturation become quantitatively identical. Carrier's observations for water wet-bulbs were explained, but were shown to be based on a remarkable natural coincidence, and not general for other gases and liquids.

These studies established the ratio of heat and mass transfer coefficients for air and water vapor. This led to Merkel's ingenious analysis of cooling tower operation and the engineering design method used today. It is remarkable that a theoretical analysis of the wet-bulb thermometer provided the basis for a simple and practical design procedure for cooling towers. Merckel's method also applies in the design of dehumidifiers.

I am sure that G. I. Taylor does not think of himself as a chemical engineer, but we need people like him in chemical engineering. In 1954 he developed a theory of longitudinal dispersion in open pipes, based on a generalized correlation of velocity profiles in turbulent flow [31]. Figure 2 indicates how well the theory works. The points and dotted curve show the dispersion of a radioactive tracer pulse after flowing 43 miles in an oil pipe-line in hilly country [13]. The solid curve is predicted by the Taylor theory. The agreement seems only fair, but is really quite remarkable in

view of the fact that the tracer took 85,000 seconds to travel the 43 miles to the test station. The predicted dispersion coefficient was $594 \text{ cm}^2/\text{sec.}$; the value required to fit the data is about twice that. The Taylor theory did not allow for pumps and elbows in the line.

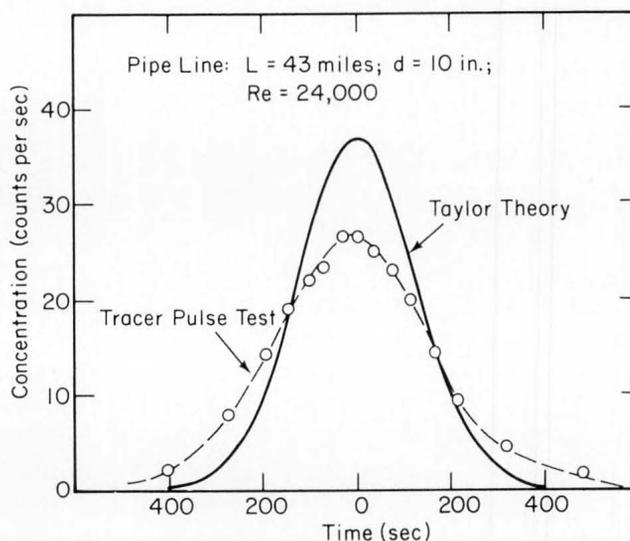


FIG. 2. Comparison between theory and experiment.

FUTURE NEEDS

WE HAVE COME A LONG WAY in fifty years, but we have much yet to do. It would seem that new complications, such as interfacial turbulence, are appearing more frequently than theory advances. In my judgment the major goal is a basic theory of the mechanism of mass transfer between phases in turbulent flow. To attain this we shall need a better understanding of flow conditions at a phase boundary. I believe chemical engineers are as likely to provide this as specialists in fluid mechanics, but it seems that it may be some years before we have it.

Of perhaps equal importance is a theory of mass transfer with simultaneous chemical reaction at a catalyst surface. The mass transfer elements of such theory are in fair shape, but surface catalysis is still an empirical art. Realizing this, chemical engineers are joining chemists in a growing program of research on catalysis. Many chemical engineering departments now have strong programs of basic research on catalysis. Perhaps the reason for this trend is the realization that the chemical reactor is the heart of the industrial chemical process, and that the unit operations are often peripheral.

Perhaps chemical engineering is emerging from an era of empiricism. Electrical engineers need only the

physical properties of their components; from there on design is a job for the computer. We have much more concern with complex physical phenomena, and we have not yet arrived at the point where all can be left to the computer. In a way I hope we never will, for chemical engineering is so much more fun when we don't know very much.

Pending the ultimate development of theory, we continue to do well. Very large plants are designed, on the basis of empiricism or half-formed theory, and operate. There are no more failures than encountered by bridge designers, who have a complete theory of stresses in a structure. Some of our industrial processes even make money, and provide our profession not only with a livelihood but satisfying careers for chemical engineers. □

SYMBOLS AND NOMENCLATURE

C	= concentration, g moles/cm ³
C _p	= heat capacity, g cal/(g mole) (°K)
D	= molecular diffusion coefficient, cm ² /sec.
E	= eddy diffusion coefficient, cm ² /sec.
E _D	= eddy diffusion coefficient for mass transfer, cm ² /sec.
E _v	= eddy viscosity, cm ² /sec.
f	= Fanning friction factor
g _c	= conversion factor (=32.2 in English system of units)
J _A	= molal diffusion flux of A in absence of superposed convection, g moles/(sec)(cm ²).
k	= thermal conductivity, g cal/(sec) (cm ²) (°K/cm)
k _c	= mass transfer coefficient, cm/sec.
P	= pressure, g/cm ²
Pr	= Prandtl number, = C _p μ/k
r	= radial distance from axis of tube, cm.
r _w	= tube radius, cm.
s	= fractional rate of surface renewal, sec ⁻¹ .
Sc	= Schmidt number, = μ/ρD = μ/D
St	= Stanton number = k _c /U _{AV}
t	= fluctuating temperature, °K
T	= time-mean temperature, °K
u	= fluctuating velocity, cm/sec.
u ⁺	= dimensionless velocity, defined by Equation 5
U _{AV}	= time-mean average velocity, cm/sec.
U _x	= time-mean velocity at a point, in x-direction, cm/sec.
x, y, x	= coordinates, cm.
y	= distance in direction of diffusion, cm.
y _o	= film thickness, cm.
y ⁺	= dimensionless distance from wall, defined by Equation 5
Y _A	= time-mean mole fraction
Y'	= fluctuating mole fraction
μ	= viscosity, g/(sec) (cm).
ν	= kinematic viscosity, = μ/ρ, cm ² /sec.
ρ	= density, g/cm ³ .

REFERENCES

1. Beddingfield, C. H. and T. B. Drew, *Ind. Eng. Chem.*, **42** 1164 (1950).
2. Brian, P. L. T., *et al.*, *A.I.Ch.E. J.*, **17** 765 (1971); **18** 231, 582 (1972).

3. Brian, P. L. T., J. F. Hurley, and E. H. Hasseltine, *A.I.Ch.E. J.*, **7** 226 (1961).
4. Brian, P. L. T., *A.I.Ch.E. J.*, **10** 5 (1964).
5. Chilton, T. H. and A. P. Colburn, *Ind. Eng. Chem.*, **26** 1183 (1934).
6. Davis, H. S., G. Thompson, and G. S. Crandall, *J. A. C. S.*, **54** 2340 (1932).
7. Danckwerts, P. V., *Ind. Eng. Chem.*, **43** 1460 (1951).
8. Danckwerts, P. V. and A. M. Kennedy, *Trans. Inst. Chem. Eng. (London)* **32**, Suppl. S 49 (1954).
9. Danckwerts, P. V., "Gas-Liquid Reactions," McGraw-Hill Book Co., New York, 1970.
10. Ellis, S. R. M. and M. Biddulf, *Chem. Eng. Sci.*, **21** 1107 (1966).
11. Friend, W. L. and A. B. Metzner, *A.I.Ch.E. J.*, **4** 393 (1958).
12. Gilliland, E. R. and T. K. Sherwood, *Ind. Eng. Chem.*, **26** 516 (1934).
13. Hull, D. E. and J. W. Kent, *Ind. Eng. Chem.*, **44**, 2745 (1952).
14. Harriott, P. and R. M. Hamilton, *Chem. Eng. Sci.*, **20** 1073 (1965).
15. Hatta, S., *Tech. Rept. Tohoku Imp. Univ.*, **8** 1 (1928-29).
16. Hightie, R., *Trans. AICHE*, **31** 365 (1935).
17. Hoftzyer, P. J. and D. W. Van Krevelen, *Trans. Inst. Chem. Eng. (London)*, **32** Suppl., 560 (1954).
18. Kline, S. J., and P. W. Runstadler, *ASME Paper* 58-A-64 (1964).
19. Lewis, J. B. and H. C. R. Pratt *171* 1155 (1953).
20. Lewis, W. K. and W. G. Whitman, *Ind. Eng. Chem.*, **16** 1215 (1924).
21. Meyerink, E. S. C. and S. K. Friedlander, *Chem. Eng. Sci.*, **17** 121 (1962).
22. Murphree, E. V., *Ind. Eng. Chem.*, **24** 726 (1932).
23. Nedderman, R. M., *Chem. Eng. Sci.*, **16** 120 (1961).
24. Notter, R. H. and C. A. Sleicher, *Chem. Eng. Sci.* **26** 161 (1971).
25. Pearson, J. K. A., *J. Fluid Mech.*, **4** 489 (1958).
26. Ramachandran, P. A. and M. M. Sharma, **24** 1681 (1969).
27. Reynolds, O., *Proc. Manchester Lit. Phil. Soc.*, **14** 7 (1874); reprinted in "Papers on Mechanical and Physical Subjects," Vol. 1, p. 81, Cambridge Univ. Press (1900).
28. Zeldowitsch, J. B., *Acta Physicochim*, U.S.R.S. **10** 1030 (1957).
29. Sherwood, T. K., K. A. Smith, and P. E. Fowles, *Chem. Eng. Sci.*, **23** 1225 (1968).
30. Sternling, C. V. and L. E. Scriven, *A.I.Ch.E. J.*, **5** 514 (1959).
31. Taylor, G. I., "Scientific Papers," G. K. Batchelor, ed. Vol. II, p. 466. Cambridge Univ. Press, 1960.
32. Thiele, E. W., *Ind. Eng. Chem.*, **31** 916 (1939).
33. Vieth, W. R., J. H. Porter, and T. K. Sherwood, *Ind. Eng. Chem. Fund.*, **2** 1 (1963).
34. Von Karman, Th., *Trans. ASME* **61** 705 (1939).
35. Wasan, D. T., C. L. Tien, and C. R. Wilke, *A.I.Ch.E. J.*, **9** 568 (1963).
36. Wasan, D. T. and C. R. Wilke, *Int. J. Heat and Mass Transfer*, **7** 87 (1964).
37. Whitman, W. G., *Chem. and Met. Eng.*, **29** 146 (1932).
38. Zeldowitsch, J. B., *Acta Physicochim*, U.R.S.S. **10** 583 (1939).

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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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PROCESS DESIGN
AND DEVELOPMENT

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MATERIAL ENGINEERING

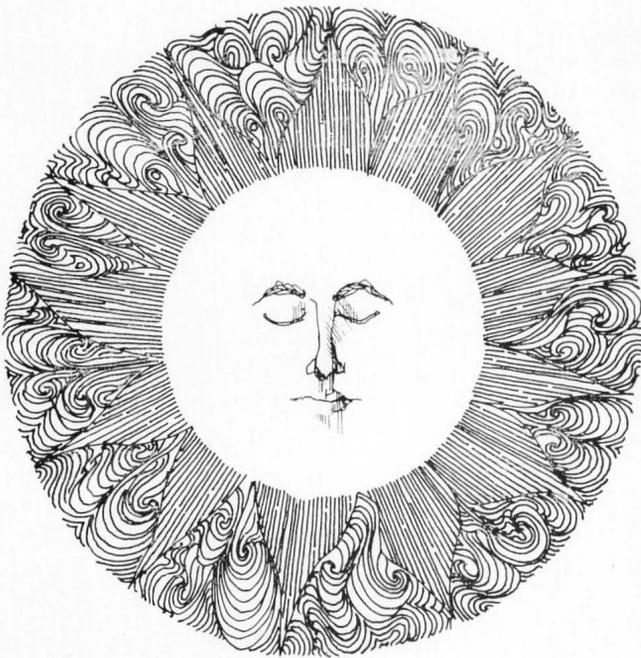
FLUID MECHANICS
AND RHEOLOGY

FACULTY

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Lee F. Donaghey
Alan S. Foss
Simon L. Goren
Edward A. Grens
Donald N. Hanson
C. Judson King (Chairman)
Scott Lynn
David N. Lyon
Robert P. Merrill
John S. Newman
Eugene E. Petersen
Robert L. Pigford
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Mitchel Shen
Thomas K. Sherwood
Charles W. Tobias
Theodore Vermeulen
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FOR APPLICATIONS AND FURTHER INFORMATION, WRITE:

Department of Chemical Engineering
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B. C. Gates	G. C. A. Schuit (1/2 time)
J. R. Katzer	J. M. Schultz
R. L. McCullough	James Wei
A. B. Metzner	

The adjunct and research faculty who provide extensive association with industrial practice are:

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W. H. Manogue	Catalysis, reaction engineering
E. L. Mongan, Jr.	Design and process evaluation
F. E. Rush, Jr.	Mass transfer—distillation, absorption, extraction
R. J. Samuels	Polymer science
A. B. Stiles	Catalysis
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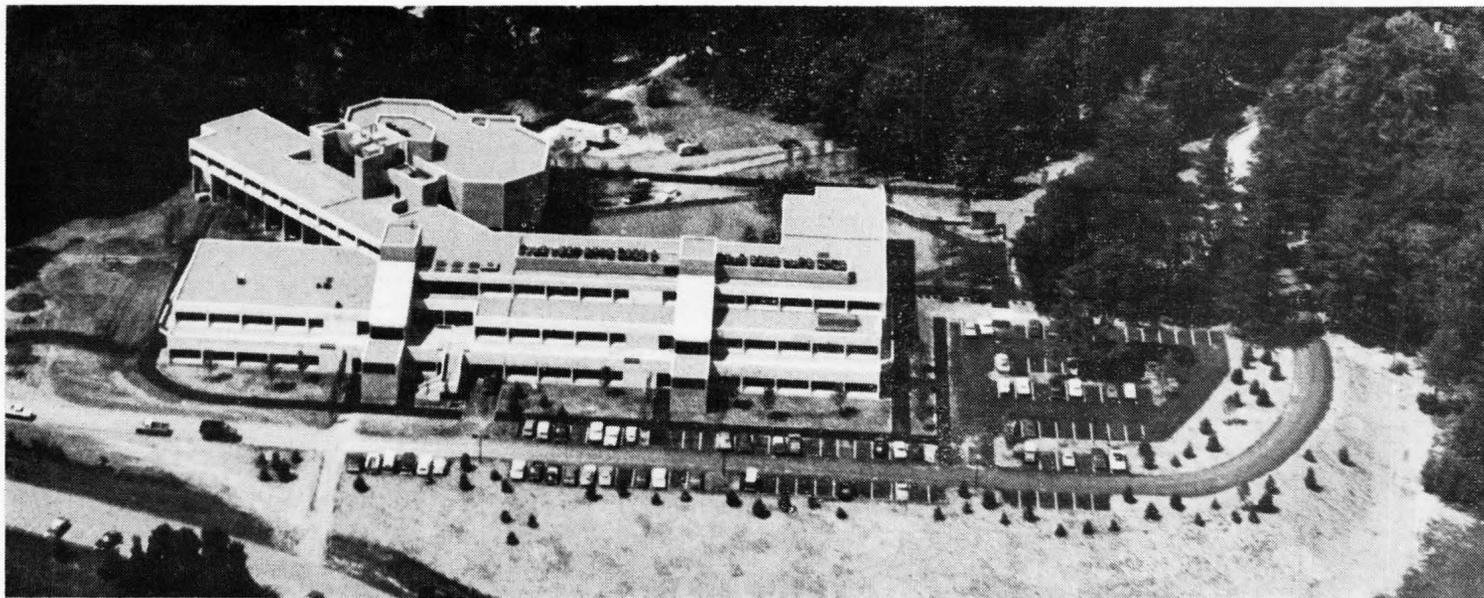


WRITE TO: R.B. Grieves, Chairman
Dept. of Chemical Engineering
UNIVERSITY OF KENTUCKY
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D. T. CHIN—Assoc. Prof. (Ph.D., 1969, University of Pennsylvania) Electrochemical engineering, transport phenomena, mass transfer at electrodes.

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

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

E. J. WOVIS—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.

J. ESTRIN—Prof. (Ph.D., 1960, Columbia University) Nucleation phenomena, crystallization.

E. W. GRAHAM—Assoc. Prof. (Ph.D., 1962, University of California, Berkeley) Chemical reaction kinetics and related theoretical problems, catalysis, fuel cells, air pollution.

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

R. A. SHAW—Assoc. Prof. (Ph.D., 1967, Cornell University) Nuclear engineering, reverse osmosis, radioactive tracers, environmental effects of power generation.

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 problems, unsteady convective diffusion—miscible dispersion, chromatographic and other interphase transport systems, fluid mechanics.

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

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

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

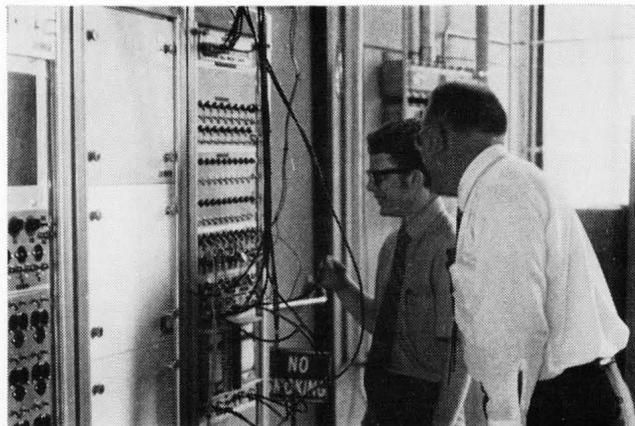
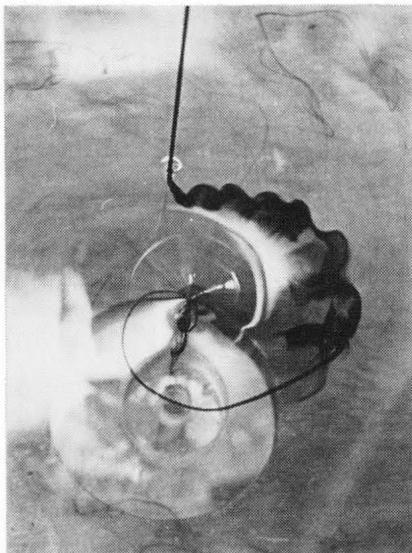
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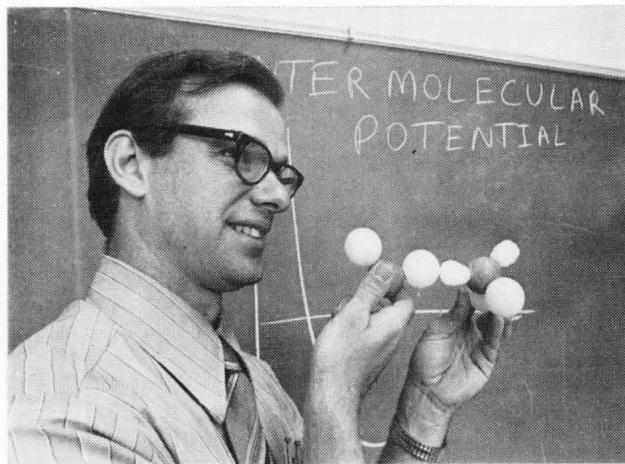
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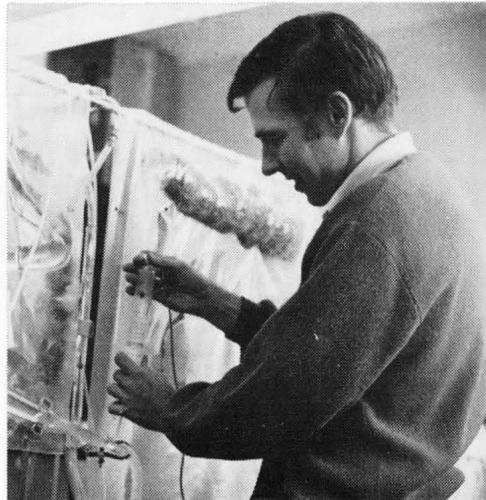
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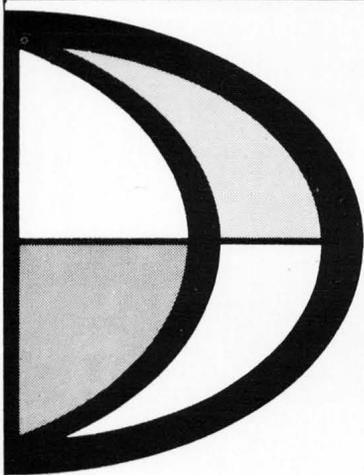
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*Dr. John C. Biery, Chairman
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University of Houston
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DOCTOR OF PHILOSOPHY

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

James P. Hartnett
Ph.D., University of California at Berkeley, 1954
Professor and Head of the Department

Larry M. Joseph
Ph.D., University of Michigan, 1974
Assistant Professor

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

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

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

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

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

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

Forced convection, mass transfer cooling,
non-Newtonian fluid mechanics and heat transfer

Process dynamics and control, simulation
and process analysis

Kinetics of gas reactions, energy transfer
processes, molecular lasers

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fluids, solids, and solutions; kinetics of liquid
reactions, cryobioengineering

Chemical engineering, bioengineering, membrane
transport processes, mathematical modeling

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

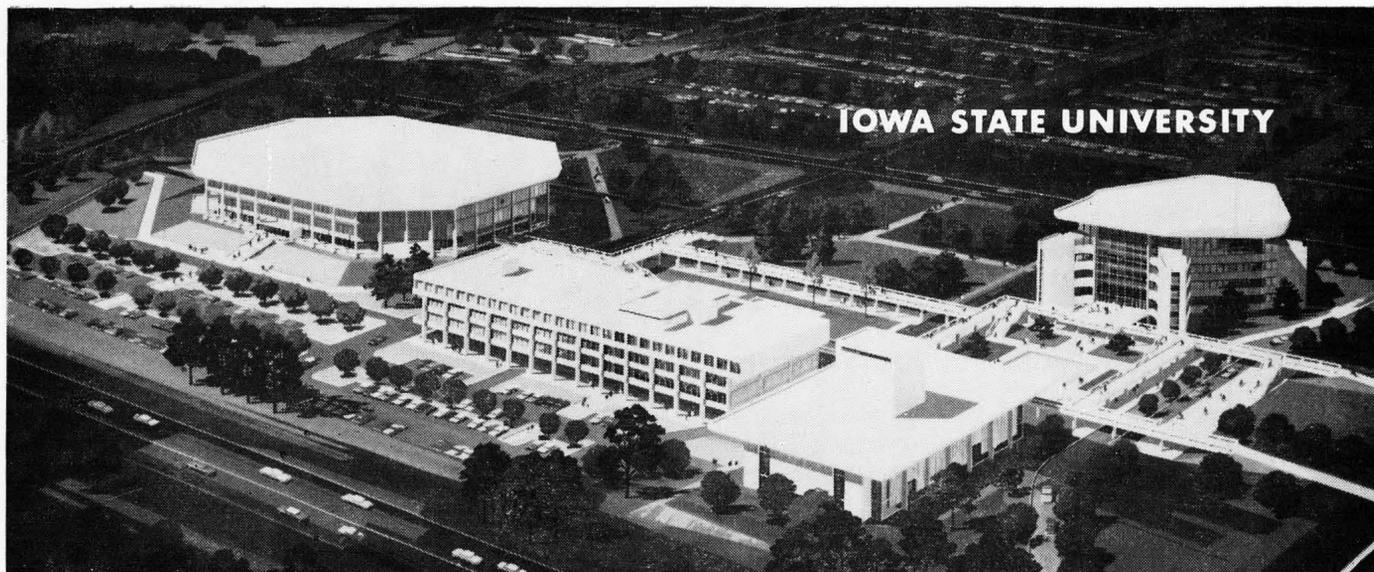
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Professor Harold A. Simon, Chairman
The Graduate Committee
Department of Energy Engineering
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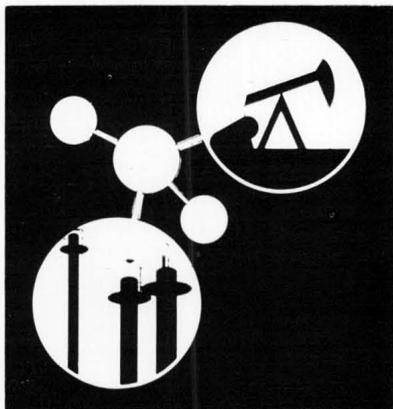
TO APPLY

Write to:

George Burnet, Head
 Dept. of Chemical Engineering and Nuclear Engineering
 Iowa State University of Science and Technology
 Ames, Iowa 50010

UNIVERSITY OF KANSAS

Department of Chemical and Petroleum Engineering



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Complex Physical Systems

Reaction Kinetics and
Process Design

Nucleate Boiling

High Pressure, Low Temperature
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For Information and Applications write:

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

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Chemical Microscopy

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Kinetics and Catalysis

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Chemical Processes and Process Control

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Faculty Members and Research Interests

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Kenneth B. Bischoff, Ph.D. Medical and microbiological bioengineering, chemical reaction engineering.

George G. Cocks, Ph.D. Light and electron microscopy, properties of materials, solid-state chemistry, crystallography.

Robert K. Finn, Ph.D. Continuous fermentation, agitation and aeration, processing of biochemicals, electrophoresis, microbial conversion of hydrocarbons.

Peter Harriott, Ph.D. Kinetics and catalysis, process control, diffusion in membranes and porous solids.

J. Eldred Hedrick, Ph.D. Economic analyses and forecasts, new ventures development.

Ferdinand Rodriguez, Ph.D. Polymerization, properties of polymer systems.

George F. Scheele, Ph.D. Hydrodynamic stability, coalescence, fluid mechanics of liquid drops and jets, convection-distorted flow fields.

Michael L. Shuler, Ph.D., Biochemical engineering.

Julian C. Smith, Chem.E. Conductive transfer processes, heat transfer, mixing, mechanical separations.

James F. Stevenson, Ph.D. Chemical engineering applications to biomedical problems; rheology.

Raymond G. Thorpe, M.Chem.E. Phase equilibria, fluid flow, kinetics of polymerization.

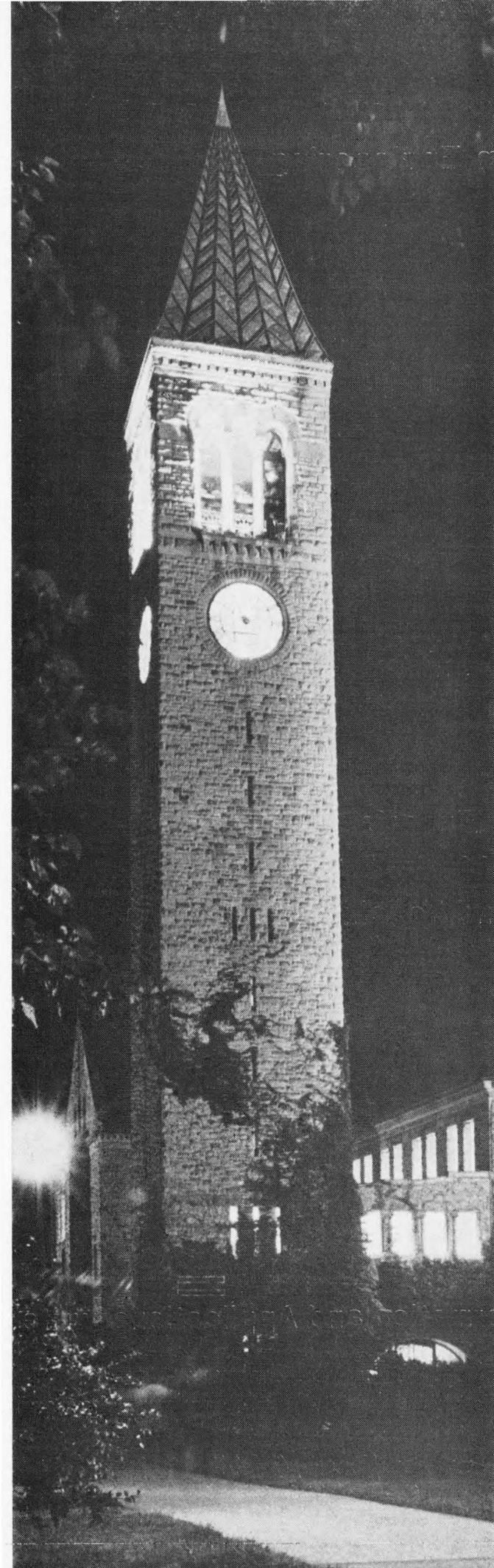
Robert L. Von Berg, Sc.D. Liquid-liquid extraction, reaction kinetics, effect of radiation on chemical reactions.

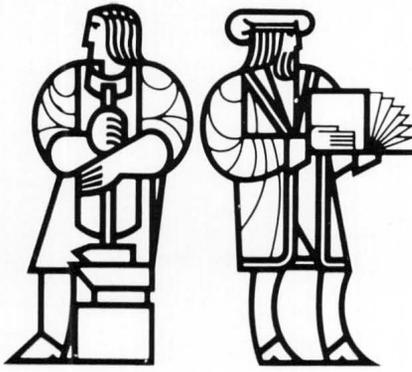
Herbert F. Wiegandt, Ph.D. Crystallization, petroleum processing, saline-water conversion, direct contact heat transfer.

Charles C. Winding, Ph.D. Degradation of polymers, polymer compounding, filler-polymer systems, differential thermal analysis.

Robert York, Sc.D. Molecular sieves, chemical market analyses, chemical economics, process development, design, and evaluation.

FURTHER INFORMATION. Write to Professor K. B. Bischoff, Olin Hall of Chemical Engineering, Cornell University, Ithaca, New York 14850.





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Paul J. Flory
Hoyt C. Hottel
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Herman P. Meissner
Edward W. Merrill
J. Th. G. Overbeek
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Department of Chemical Engineering

UNIVERSITY OF MISSOURI — ROLLA

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Contact Dr. M. R. Strunk, Chairman

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—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
- (5) Structure and Properties of Polymers—Dr. K. G. Mayhan

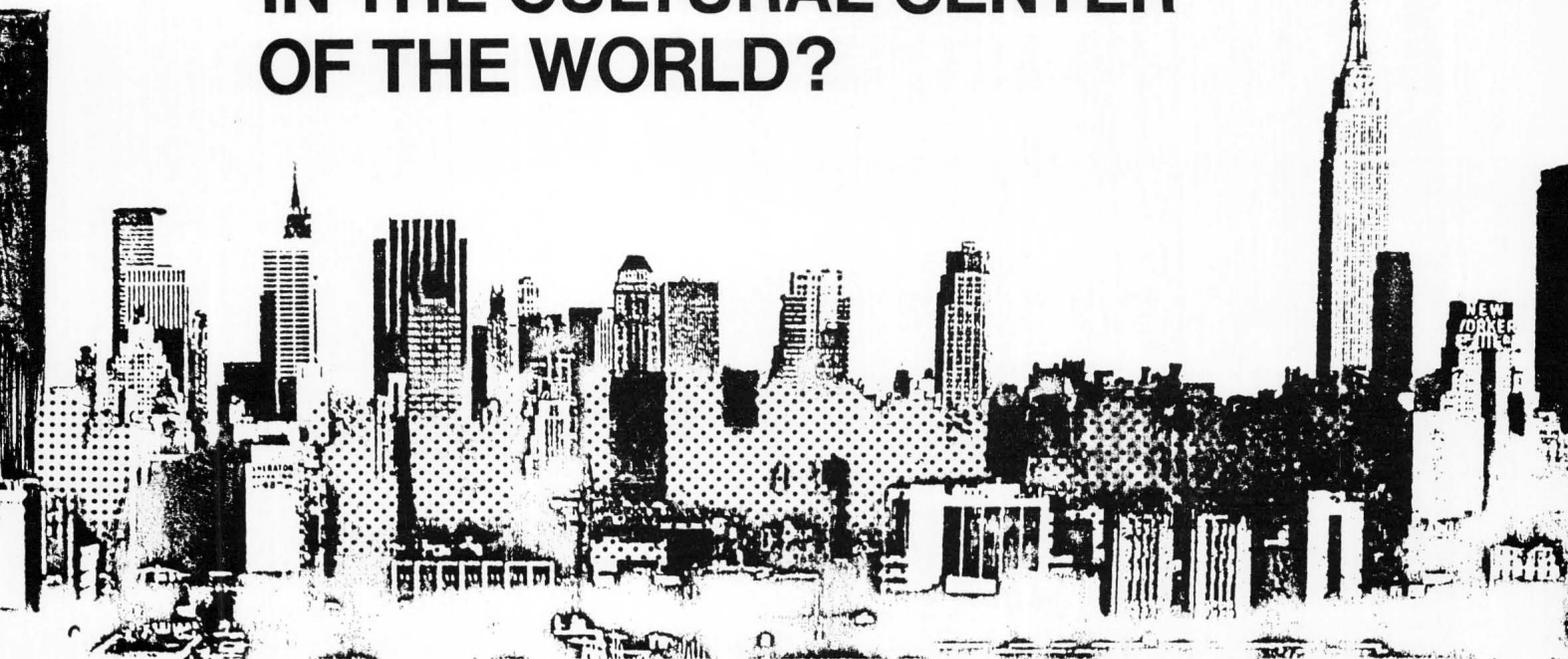
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- (b) Evaporation through non-Wettable Porous Membranes—Dr. M. E. Findley
- (c) Multi-component Distillation Efficiencies—Dr. R. C. Waggoner
- (d) Gas Permeability Studies—Dr. R. A. Primrose
- (e) Separations by Electrodialysis Techniques—Dr. H. H. Grice
- (f) Process Dynamics and Control—Drs. M. E. Findley, R. C. Waggoner, and R. A. Mollenkamp
- (g) Transport Properties, Kinetics and enzymes and catalysis—Dr. O. K. Crosser and Dr. B. E. Poling
- (h) Thermodynamics, Vapor-Liquid Equilibrium—Dr. D. B. Manley



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Department of Chemical Engineering

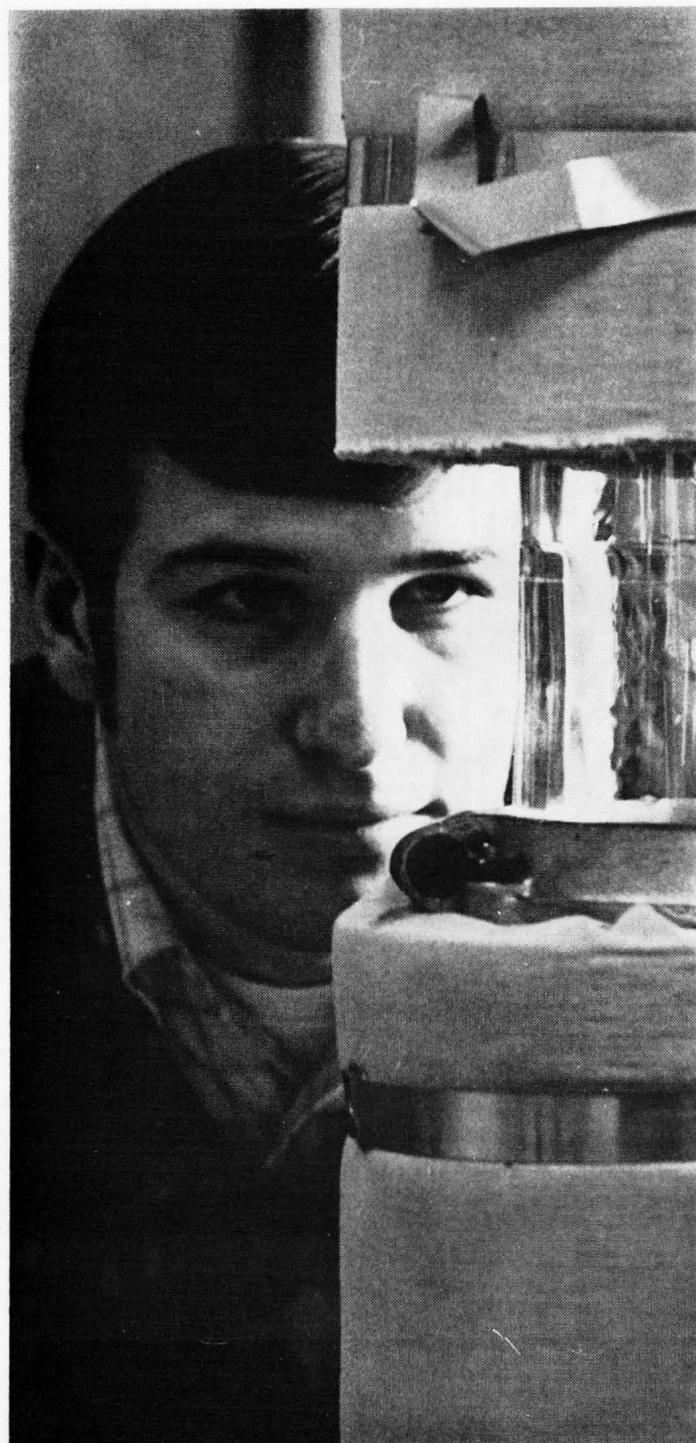
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160 Chemical Engineering Building
The Pennsylvania State University
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DEPARTMENT OF CHEMICAL AND BIOCHEMICAL ENGINEERING

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FACULTY

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Elizabeth Dussan V. (Johns Hopkins)
William C. Forsman (Pennsylvania)
David J. Graves (M.I.T.)
A. Norman Hixson (Columbia)
Arthur E. Humphrey (Columbia)
Ronald L. Klaus (R.P.I.)

Mitchell Litt (Columbia)
Alan L. Myers (California)
Melvin C. Molstad (Yale)
Leonard Nanis (Columbia)
Daniel D. Perlmutter (Yale)
John A. Quinn (Princeton)
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Biomedical Engineering
Computer-Aided Design
Chemical Reactor Analysis
Electrochemical Engineering

Environmental and Pollution Control
Polymer Engineering
Process Simulation
Surface Phenomena
Separations Techniques
Biochemical Engineering

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

Department of Chemical Engineering

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Faculty

R. P. Andres—Molecular beams, intermolecular forces, microparticles, nucleation phenomena.

R. C. Axtmann—Fusion reactor technology, environmental studies of fusion and geothermal power, synthetic fuel production.

R. L. Bratzler—Bioengineering: cardiovascular transport phenomena, extra corporeal devices.

John K. Gillham—Mechanical spectrometry of polymeric solids, synthesis, characterization and pyrolysis of polymers.

E. F. Johnson—Fusion reactor technology, molten salts (kinetic and thermodynamic properties, catalysis), process control.

M. D. Kostin—Chemical kinetics, bioengineering, transport phenomena, applications of quantum theory.

Leon Lapidus—Numerical analysis in chemical engineering, computer-aided design techniques, identification and control of reaction systems.

Bryce Maxwell—Shear-induced crystallization of polymers, melt structure recovery, polymer mixing and blending.

D. F. Ollis—Heterogeneous and homogeneous catalysis, biochemical engineering.

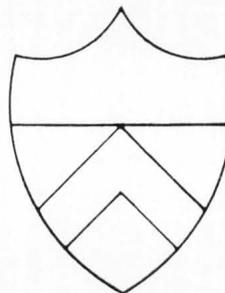
William B. Russel—Fluid mechanics, dynamics of colloidal systems.

D. A. Saville—Fluid mechanics, behavior of particulate systems, electrical phenomena in fluids.

W. R. Schowalter—Fluid mechanics, rheology.

N. H. Sweed—Fixed bed sorption processes, chemical reactor engineering, honeycomb catalysts, coal processing (gasification and liquifaction).

G. L. Wilkes—Morphology and properties of block and segmented copolymers, crystallization of polymers, biopolymers and biomaterials.



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



RENSSELAER POLYTECHNIC INSTITUTE

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HEAT TRANSFER
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PROCESS DYNAMICS
BIOMEDICAL ENGINEERING**

Rensselaer Polytechnic Institute, established in 1824 "for the application of science to the common purposes of life," has grown from a school of engineering and applied science into a technological university, serving some 3500 undergraduates and over 1000 graduate students.

It is located in Troy, New York, about 150 miles north of New York City and 180 miles west of Boston. Troy, Albany, and Schenectady together comprise the heart of New York's Capital District, an upstate metropolitan area of about 600,000 population. These historic cities and the surrounding countryside provide the attractions of both urban and rural life.

Scenic streams, lakes and mountains, including the Hudson River, Lake George, the Green Mountains of Vermont, the Berkshires of Massachusetts, and portions of the Adirondack Forest Preserve, are within easy driving distance, and offer many attractions for those interested in skiing, hiking, boating, hunting, fishing, etc.

For full details write Mr. R. A. Du Mez, Director of Graduate Admissions, Rensselaer Polytechnic Institute, Troy, New York 12181.



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 35 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

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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 September 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.

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Dr. M. W. Davis, Jr., Chairman
Chemical Engineering Program
College of Engineering
University of South Carolina
Columbia, S. C. 29208

THE CHEMICAL ENGINEERING FACULTY

B. L. Baker, Professor, Ph.D., North Carolina State University, 1955 (Process design, environmental problems, ion transport)

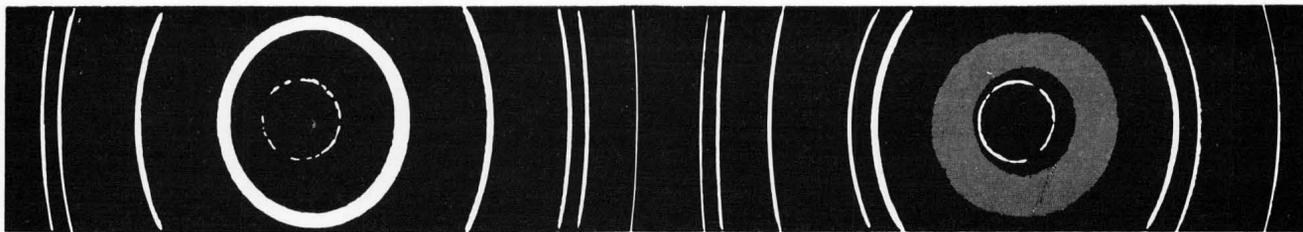
M.W. Davis, Jr., Professor, Ph.D., University of California (Berkeley), 1951 (Kinetics and catalysis, chemical process analysis, solvent extraction, waste treatment)

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

P. E. Kleinsmith, Assistant Professor, Ph.D., Carnegie-Mellon University, 1972 (Transport phenomena, statistical mechanics)

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

J. M. Tarbell, Assistant Professor, Ph.D., University of Delaware, 1974 (Thermodynamics, process dynamics)



THE UNIVERSITY OF TENNESSEE

Programs

Programs for the degrees of Master of Science and Doctor of Philosophy are offered in both Chemical and Metallurgical Engineering. The Master's program may be tailored as a terminal one with emphasis on professional development, or it may serve as preparation for more advanced work leading to the Doctorate. Specialization in Polymer Science and Engineering is available at both levels.

Faculty

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

Graduate Studies in Chemical & Metallurgical Engineering

Research

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Sorption Kinetics and Dynamics of
Packed Beds
Chromatographic and Ultracentrifuge
Studies of Macromolecules
Development and Synthesis of New
Engineering Polymers
Fiber and Plastics Processing
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



CHEMICAL ENGINEERING

DEGREES: M.S., Ph.D.

RESEARCH AREAS INCLUDE:

- HEAT AND MASS TRANSFER
- REACTION KINETICS AND CATALYSIS
- PROCESS DYNAMICS AND CONTROL
- PROCESS MODELING

IN: COAL GASIFICATION, WOOD PYROLYSIS, METHANATION, ECOSYSTEM ANALYSIS, AND THEORETICAL STUDIES

CONTACT: DR. WILLIAM J. HATCHER, JR., HEAD
P. O. Box 6312
University, Alabama 35486



AUBURN UNIVERSITY

A Land Grant University of Alabama

GRADUATE STUDY IN CHEMICAL ENGINEERING

M.S. AND PH.D. DEGREES

CURRENT RESEARCH AREAS:

- LIQUID FUELS FROM COAL
- POROUS MEDIA
- CRYSTAL GROWTH KINETICS
- INDUSTRIAL WASTEWATER TREATMENT
- PROCESS CONTROL
- P-V-T RELATIONS
- SOLIDS-LIQUID SEPARATION
- TRANSPORT PHENOMENA

Financial Assistance:

Research and Teaching Assistantships,
Industrial Fellowships Are Available

For Further Information, Write:

Head, Chemical Engineering Department
Auburn University, Auburn, Alabama 36830

BRIGHAM YOUNG UNIVERSITY

Chemical Engineering Department M.S. AND Ph.D. PROGRAMS

Areas of Interest

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Thermodynamics
(Center for thermochemical studies)
High pressure technology
Environmental quality control
Energy resources
(Combustion Research Center)
Nuclear Engineering
Catalysis
Fluid Mechanics

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Research Assistantships
Teaching Assistantships
Scholarships
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Calvin H. Bartholomew
James J. Christensen
Ralph L. Coates
Joseph M. Glassett
H. Tracy Hall
Richard W. Hanks

M. Duane Horton
James F. Jackson
John L. Oscarson
Bill J. Pope
L. Douglas Smoot
Grant M. Wilson

**FOR INFORMATION CONTACT:
Dr. Richard W. Hanks
350G ESTB, Chemical Engineering
Brigham Young University
Provo, Utah 84601**



DEPARTMENT OF CHEMICAL ENGINEERING

BUCKNELL UNIVERSITY

LEWISBURG, PENNSYLVANIA 17837

For admission, address

Dr. Paul H. DeHoff

Coordinator of Graduate Studies

- Graduate degrees granted: Master of Science in Chemical Engineering
- Some courses for graduate credit are available in the evenings.
- Typical research interests of the faculty include the areas of: mass transfer, particularly distillation, solid-liquid, and liquid-liquid extraction; thermodynamics; reaction kinetics; catalyst deactivation; process dynamics and control; metallurgy and the science of materials; mathematical modeling; numerical analysis; statistical analysis.
- Assistantships and scholarships are available.
- For the usual candidate, with a B.S. in Chemical Engineering, the equivalent of thirty semester-hours of graduate credit including a thesis is the requirement for graduation.

UNIVERSITY OF CALIFORNIA, DAVIS

CHEMICAL ENGINEERING, M.S. AND PH.D. PROGRAMS

Faculty

R. L. Bell:	Mass Transfer, Bio Medical Engineering
R. G. Carbonell	Enzyme Kinetics, Quantum Mechanics
A. P. Jackman:	Process Dynamics, Thermal Pollution
B. J. McCoy:	Molecular Theory, Transport Processes
J. M. Smith:	Water Pollution, Reactor Design
S. Whitaker:	Fluid Mechanics, Interfacial Phenomena

To Receive Applications for Admission and Financial Aid Write To:

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



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CHEMICAL AND NUCLEAR ENGINEERING

Henri J. Fenech
Owen T. Hanna
Duncan A. Mellichamp
John E. Myers

G. Robert Odette
A. Edward Profio
Robert G. Rinker
Orville C. Sandall

For information, please write to: Department of Chemical and Nuclear Engineering
University of California, Santa Barbara 93106

Case Institute of Technology

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

Current Research Topics

Environmental Engineering
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Simulation and Control
Catalysis and Surface Chemistry

Crystal Growth and Materials
Engineering Applications of Lasers
Process Development
Biomedical Engineering

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Case Institute of Technology is a privately endowed institution with a tradition of excellence in Engineering and Applied Science since 1880. In 1967 Case Institute and Western Reserve University joined together. The enrollment, endowment and faculty make Case Western Reserve University one of the leading private schools in the country. The modern, urban campus is located in Cleveland's University Circle, an extensive concentration of education, scientific, social and cultural organizations.

For more information, contact: Graduate Student Advisor

Department of Chemical Engineering
Case Western Reserve University
Cleveland, Ohio 44106

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Inquiries to: Dr. David B. Greenberg, Head
Dept. of Chemical & Nuclear Engineering
University of Cincinnati
Cincinnati, Ohio 45221



CLEMSON UNIVERSITY

Chemical Engineering Department

M.S. and Doctoral Programs

THE FACULTY AND THEIR INTERESTS

Alley, F. C., Ph.D., U. North Carolina—Air Pollution, Unit Operations
Barlage, W. B., Ph.D., N. C. State—Transfer Processes in Non-Newtonian Fluids
Beard, J. N., Ph.D., L.S.U., Chemical Kinetics, Hybrid Computation
Beckwith, W. F., Ph.D., Iowa State—Transport Phenomena
Edie, D. D., Ph.D., U. Virginia—Polymay
Harshman, R. C., Ph.D., Ohio State—Chemical and Biological Kinetics, Design
Littlejohn, C. E., Ph.D., V.P.I.—Mass Transfer
Melsheimer, S.S., Ph.D. Tulane—Process Dynamics, Applied Mathematics
Mullins, J. C., Ph.D., Georgia Tech—Thermodynamics, Adsorption

FINANCIAL ASSISTANCE—Fellowships, Assistantships, Traineeships

Contact:

C. E. Littlejohn, Head
Department of Chemical Engineering
Clemson University
Clemson, S. C. 29631

THE CLEVELAND STATE UNIVERSITY



MASTER OF SCIENCE PROGRAM IN CHEMICAL ENGINEERING

AREAS OF SPECIALIZATION

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FOR FURTHER INFORMATION, PLEASE CONTACT:

Department of Chemical Engineering
The Cleveland State University
Euclid Avenue at East 24th Street
Cleveland, Ohio 44115

the university of connecticut

faculty

J. P. BELL
C. O. BENNETT
M. B. CUTLIP
A. T. DiBENEDETTO
G. M. HOWARD
H. E. KLEI
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Department of Chemical Engineering
The University of Connecticut
Storrs, Connecticut 06268

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R. E. Peck	Heat Transfer and Thermodynamics
B. S. Swanson	Process Dynamics and Controls
L. L. Tavlarides	Biochemical Engineering and Reactor Engineering
J. S. Vrentas	Polymer Science and Transport Phenomena
D. T. Wasan	Mass Transfer and Particle Dynamics
H. Weinstein	Biomedical Engineering and Reactor Engineering

For inquiries write to: D. T. Wasan, Chairman

**Chemical Engineering Department
Illinois Institute of Technology
10 West 33rd Street
Chicago, Illinois 60616**

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FOR MORE INFORMATION WRITE TO

Professor B. G. Kyle
 Department of Chemical Engineering
 Kansas State University
 Manhattan, Kansas 66502

AREAS OF STUDY AND RESEARCH

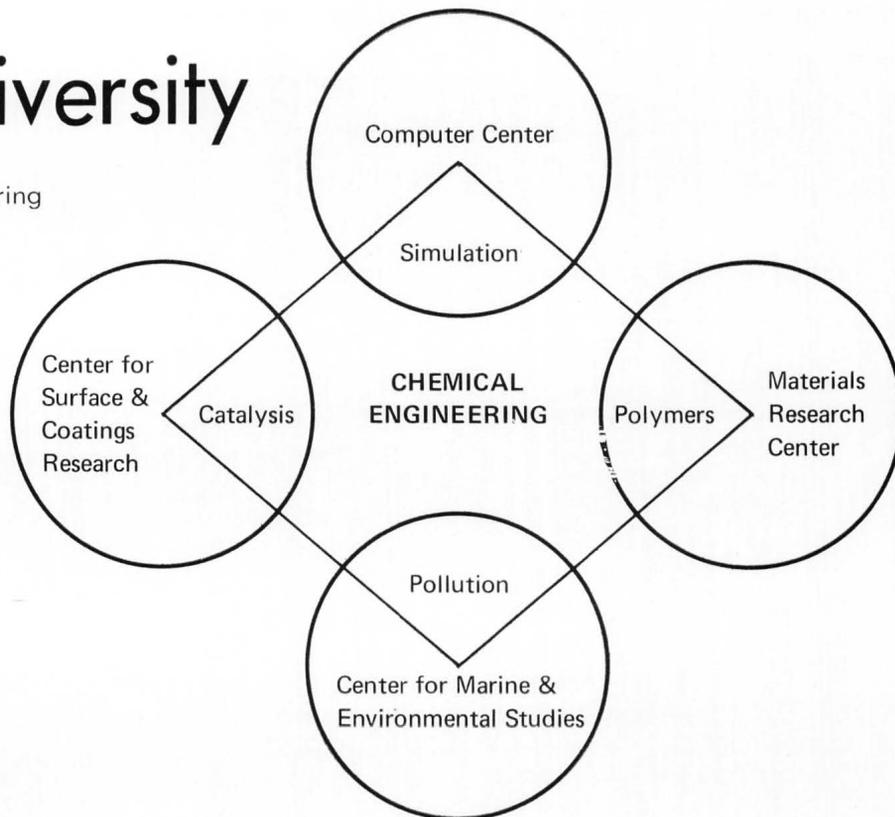
DIFFUSION AND MASS TRANSFER
 HEAT TRANSFER
 FLUID MECHANICS
 THERMODYNAMICS
 BIOCHEMICAL ENGINEERING
 PROCESS DYNAMICS AND CONTROL
 CHEMICAL REACTION ENGINEERING
 MAGNETOHYDRODYNAMICS
 SOLID MIXING
 DESALINATION
 OPTIMIZATION
 FLUIDIZATION
 PHASE EQUILIBRIUM

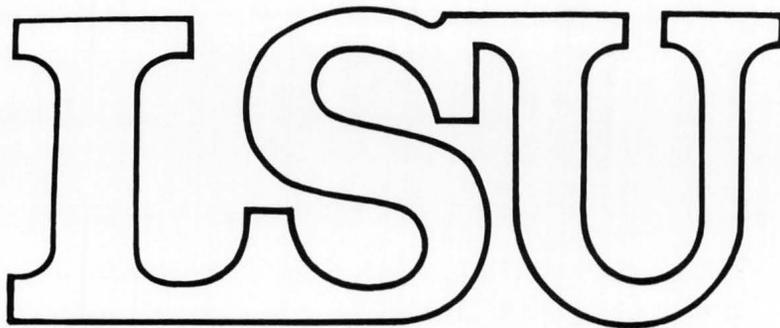
Lehigh University

Department of Chemical Engineering

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 C. W. CLUMP
 R. W. COUGHLIN
 A. S. FOUST
 W. L. LUYBEN
 A. J. McHUGH
 G. W. POEHLEIN
 W. E. SCHIESSER
 L. H. SPERLING
 F. P. STEIN
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Bethlehem, Pa. 18015





Graduate Enrollment — 80

Faculty — 19

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

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

McMASTER UNIVERSITY

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

THE FACULTY AND THEIR INTERESTS

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M. H. I. Baird (Ph.D., Cambridge)	Oscillatory Flows, Transport Phenomena
A. Benedek (Ph.D., U. of Washington)	Wastewater Treatment, Novel Separation Techniques
J. L. Brash (Ph.D., Glasgow)	Polymer Chemistry, Use of Polymers in Medicine
C. M. Crowe (Ph.D., Cambridge)	Optimization, Chemical Reaction Engineering, Simulation
I. A. Feuerstein (Ph.D., Massachusetts)	Biological Fluid and Mass Transfer
A. E. Hamielec (Ph.D., Toronto)	Polymer Reactor Engineering, Transport Processes
J. W. Hodgins (Ph.D., Toronto)	Polymerization, Applied Chemistry
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
T. Wairegi (Ph.D., McGill)	Fluid Mechanics, (Bubbles, drops and Solid Particles)
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. J. W. Hodgins, Chairman
Department of Chemical Engineering
Hamilton, Ontario, Canada L8S 4L7**

MICHIGAN TECHNOLOGICAL UNIVERSITY



DEPARTMENT OF CHEMISTRY
AND CHEMICAL ENGINEERING
HOUGHTON, MICHIGAN 49931

CHEMICAL ENGINEERING FACULTY

L. B. HEIN, Ph.D., Department Head

DEGREES GRANTED: M.S.

M. W. BREDEKAMP, Ph.D. — Instrumentation, Process Dynamics and Control
E. R. EPPERSON, M.S. — Phase Equilibria
D. W. HUBBARD, Ph.D. — Lake Studies, Mixing Phenomena, Turbulent Flow
J. T. PATTON, Ph.D. — Biosynthesis, Waste Treatment, Petroleum Recovery
A. J. PINTAR, Ph.D. — Energy Conversion, Transport Phenomena, Applied Mathematics
J. M. SKAATES, Ph.D. — Fluid-Solid Reactions, Catalysis, Reactor Design
E. T. WILLIAMS, Ph.D. — Improvement of Pulpwood Yield

Financial assistance available in the form of Fellowships and Assistantships.

For more information, write to:

DR. L. B. HEIN, Head
Department of Chemistry and Chemical Engineering
MICHIGAN TECHNOLOGICAL UNIVERSITY
HOUGHTON, MICHIGAN 49931



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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

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Applications are invited for Monash University Research Scholarships tenable in the Department of Chemical Engineering. The awards are intended to enable scholars to carry out under supervision, a programme of full-time advanced studies and research which may lead to the degrees of Master of Engineering Science and/or Doctor of Philosophy.

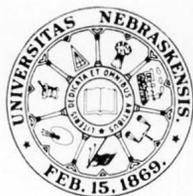
Facilities are available for work in the general fields of:

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Crystal Nucleation and Growth
Fluidisation
Rheology
Computer Control and Optimisation

Gas Absorption with Reaction
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Process Dynamics
Biochemical Engineering
Fluid - Particle Mechanics
Mixing of Liquids
Submerged Combustion

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Crystallization	Thermodynamics
Food Processing	Tray Efficiencies and Dynamics
Kinetics	and other areas

FOR APPLICATIONS AND INFORMATION ON
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Prof W. A. Scheller, Chairman, Department of Chemical Engineering
University of Nebraska, Lincoln, Nebraska 68508



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Fredericton is situated in the scenic Saint John river valley. Excellent recreational facilities including sailing, skiing, hunting and fishing are all available within a few minutes drive from the campus.

The Faculty and their Research Interests

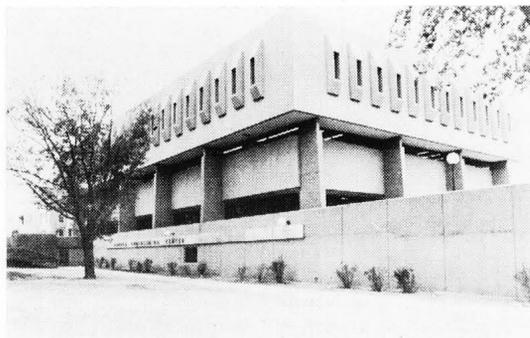
D. D. Kristmanson (Ph.D. London)	. . .	Mixing, pollution control
J. Landau (Ph.D. Prague)	. . . . .	Mass transfer, liquid extraction
K. F. Loughlin (Ph.D. U.N.B.)	. . . . .	Molecular sieves
C. Moreland (Ph.D. Birmingham)	. . . . .	Fluid-solid systems, process dynamics
D. R. Morris (Ph.D. London)	. . . . .	Electrochemistry, Corrosion
J. J. C. Picot (Ph.D. Minnesota)	. . . . .	Transport phenomena in liquid crystals
D. M. Ruthven (Ph.D. Cambridge)	. . . . .	Sorption and diffusion in molecular sieves; adsorption separation processes
F. R. Steward (Sc.D. M.I.T.)	. . . . .	Combustion, radiation, furnace design and fire science

For further information write to:

**D. M. Ruthven
Department of Chemical Engineering
University of New Brunswick
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Dept. of Chemical and Nuclear Engineering
The University of New Mexico
Albuquerque, New Mexico 87131**

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

Faculty and research interests:

J. A. Bergantz	energy sources, gas-solid reactions
D. R. Brutvan	staged operations
H. T. Cullinan, Jr.	multicomponent mass transfer, transport properties
P. Ehrlich	polymeric materials, thermodynamics
W. N. Gill	dispersion, reverse osmosis
R. J. Good	surface phenomena, adhesion of living cells
J. A. Howell	biological reactors, waste treatment
K. M. Kiser	blood flow, turbulence, pollution in lakes
P. J. Phillips	polymer morphology, structure and properties
W. H. Ray	optimization, polymerization reactors
E. Ruckenstein	catalysis, interfacial phenomena, bioengineering
J. Szekely	process metallurgy, gas-solid and solid-solid reactions
T. W. Weber	process control, dynamics of adsorption
S. W. Weller	catalysis, catalytic reactors

Financial aid is available

For full information and application materials, please contact:

Dr. Harry T. Cullinan, Jr.
Chairman, Department of Chemical Engineering
State University of New York at Buffalo
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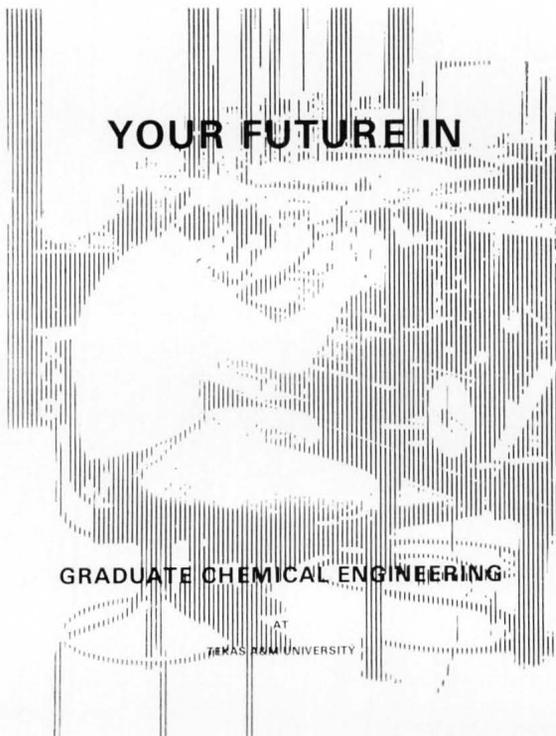
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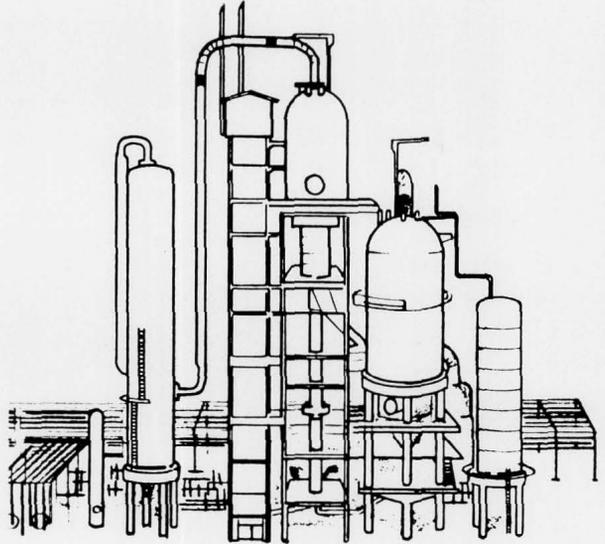
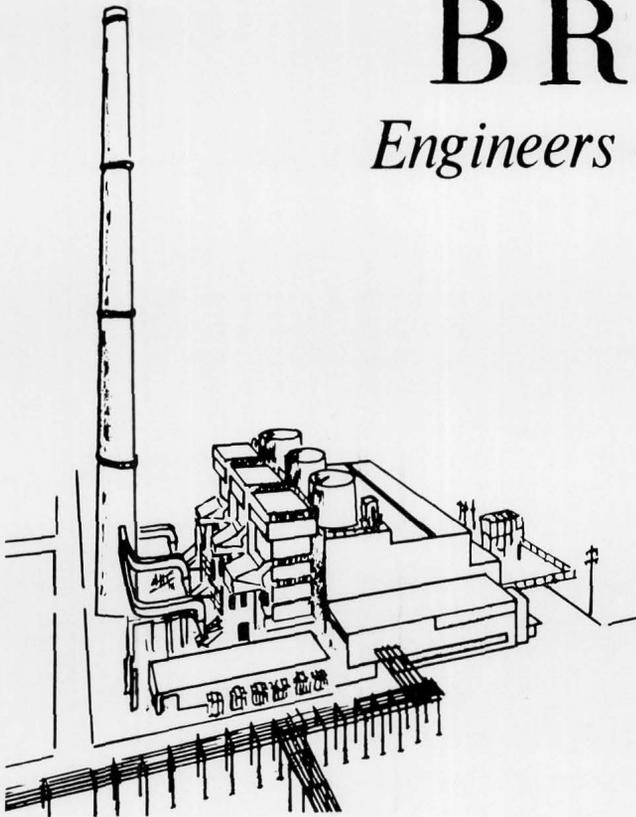
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