



GRADUATE EDUCATION ISSUE

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Also...

BOB BIRD ON
BOOK WRITING AND CHE EDUCATION

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Editor's Note

This is the 15th Graduate Issue to be published by CEE and distributed to chemical engineering seniors interested in and qualified for graduate school. As in our previous issues, we include articles on graduate courses and research at various universities and announcements of departments on their graduate programs. In order for you to obtain a broad idea of the nature of graduate work, we encourage you to read not only the articles in this issue, but also those in previous issues. A list of the papers from recent years follows. If you would like a copy of a previous Fall issue, please write CEE.

Ray Fahien, Editor, CEE
University of Florida

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Fall 1979

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Manning	"Industrial Pollution Control"
McCoy	"Separation Process"
Walter	"Enzyme Catalysis"

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A Course in

NUMERICAL METHODS AND MODELING

MARK E. DAVIS

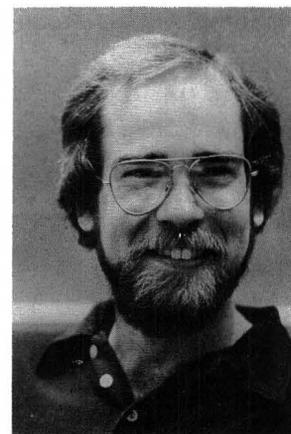
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State University
Blacksburg, VA 24061

AN ENGINEER WORKING on a mathematical project is typically not interested in sophisticated theoretical treatments, but rather the solution of a model and the physical insight that the solution can give. A recent and important tool in regards to this objective is mathematical software, i.e., preprogrammed, reliable computer subroutines for solving mathematical problems. Since numerical methods are not infallible, a "black-box" approach of using these subroutines can be dangerous. In order to utilize software effectively, one must be aware of its capabilities and especially its limitations. This implies that the user must at least have an intuitive understanding of how the software is designed and implemented.

TABLE 1

Table of Contents for Ordinary Differential Equations

1. Initial Value Problems for Ordinary Differential Equations
 - Explicit Methods
 - Stability
 - Runge-Kutta Methods
 - Implicit Methods
 - Extrapolation
 - Multistep Methods
 - Stiffness
 - Systems of Differential Equations
 - Step-Size Strategies
 - Mathematical Software
2. Boundary Value Problems for Ordinary Differential Equations: Discrete Variable Methods
 - Initial Value Methods
 - Shooting Methods
 - Superposition
 - Finite Difference Methods
 - Mathematical Software
3. Boundary Value Problems for Ordinary Differential Equations: Finite Element Methods
 - Piecewise Polynomial Functions
 - B-splines
 - Galerkin
 - Collocation
 - Mathematical Software



Mark Davis is an Assistant Professor of the Department of Chemical Engineering at Virginia Polytechnic Institute and State University since 1981. He earned his B.S., M.S. and Ph.D. (1981) from the University of Kentucky. He is currently working on research projects in zeolite catalysis, novel catalytic reactor configurations, and the application of computers to the study of reacting systems. He recently completed his first textbook in the field of mathematical modeling and is currently working on another which will involve the use of personal computers.

BACKGROUND

Typically, graduate students have time for only one or two courses in computational methods. Thus a one-semester course or a two-quarter sequence is about the maximum length compatible with most graduate programs of study. Within this limited time, the student must be exposed to the broad and rapidly increasing field of numerical methods. Traditional courses in applied numerical analysis have concentrated on algorithms, and students wrote their own programs to solve assigned problems. This approach is very time intensive and limits the scope of topics which can be covered within the timeframe outlined above. On the other extreme, there are courses which are based solely on the application of software. The increased student productivity and the expanded number of topics that can be discussed through the use of this scheme are achieved at the expense of understanding numerical methods. Also, this approach leaves the engineer at the complete mercy of software. Therefore, a course in numerical methods and modeling for chemical engineers should involve software, but give emphasis on the

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TABLE 2**Table of Contents for Partial Differential Equations**

1. Parabolic Partial Differential Equations In One Space Variable
 - Classification of Partial Differential Equations
 - Method of Lines
 - Finite Differences
 - Finite Elements
 - Galerkin
 - Collocation
 - Mathematical Software
2. Partial Differential Equations In Two Space Variables
 - Elliptic PDE's—Finite Differences
 - Elliptic PDE's—Finite Elements
 - Parabolic PDE's in Two Space Variables
 - Method of Lines
 - Alternating Direction Implicit Methods
 - Mathematical Software

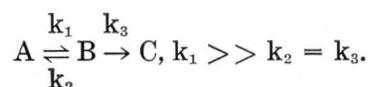
numerical techniques implemented in the software. Students should be provided with an understanding of how software is constructed and implemented in order to gain maximum benefit from it. A course of this nature bridges the gap between the aforementioned extremes in order to combine increased productivity without loss of understanding. Such courses have been developed at Virginia Polytechnic Institute and State University (VPI & SU) and are described below.

COURSE CONTENTS

A two-quarter sequence of courses in numerical methods and modeling for chemical engineers has recently been developed at VPI & SU. The courses involve the solution of differential equations since this area arises most frequently in practice, and is usually the weak point of a student's mathematical literacy. In the first quarter, ordinary differential equations are covered (see Table 1 for course contents), while in the second quarter partial differential equations are addressed (see Table 2 for course contents). Emphasis is placed on the treatment of numerical methods implemented in commercial software, and topics are covered through the use of chemical engineering examples. A textbook to support courses of this nature will be available shortly [1].

Referring to Tables 1 and 2, a few remarks on the course contents follow. Let us consider topic 1 to illustrate the methodology used throughout the courses. Topic 1 concerns initial value problems and begins with a presentation of the simplest method, namely, the Euler method. The technique is illustrated by solving an isothermal, heterogeneous, plug-flow reactor problem. The re-

actor material balance equation is formulated, and the solutions are chosen to show the low order of accuracy and the poor stability of the Euler method. These results lead into discussions concerning improvements in accuracy and stability. Runge-Kutta, implicit methods, extrapolation, and multistep methods are outlined in this context. In most cases, the topics are presented through the use of chemical engineering problems: e.g., Runge-Kutta; temperature response of a thermocouple, extrapolation; batch distillation. Before covering systems of equations, stiffness is illustrated by calculating the concentration-time profiles of the reaction network



These results are used to show why explicit methods are not suitable for stiff systems of initial value problems. To create a system of initial value equations, the plug-flow reactor problem used to demonstrate the Euler method is now specified to be adiabatic. Thus, an energy balance is added to the material balance giving a set of coupled, nonlinear initial value equations. The stiffness of the system is calculated and various methods are formulated for the solution of the problem. Next, advanced techniques such as adaptive step-size strategies and error control are covered with an emphasis on how they are implemented in software.

Finally, each topic is concluded with a survey of software. The survey used for Topic 1 is given in Table 3. Each piece of software is discussed in the context of which methods it implements, and what other features such as error control and

TABLE 3
Survey of Software for Initial Value Problems

CODE	REFERENCE
RKF45	(2)
GERK	(3)
DE/ODE	(4)
DEROOT/ODERT	(4)
GEAR/GEARB	(5, 6)
LSODE	(7)
EPISODE/EPISODEB	(8)
M3RK	(9)
STRIDE	(10)
STIFF3	(11)
BLSODE	(12)
STINT	(13)
SECDER	(14)
DVERK	(15)
DGEAR	(15)

... a course in numerical methods and modeling for chemical engineers should involve software, but give emphasis on the numerical techniques implemented in the software.

adaptive step-size abilities are incorporated. The section on mathematical software is ended by solving two reaction engineering problems chosen to illustrate stiffness. The software given in Table 3 is used to solve the two problems. The solutions are rationalized in terms of their physical implications, and the software's performance is analyzed. It is shown that software which implements explicit methods is not suitable for stiff problems. Thus, the student becomes aware of how the software is constructed and how it works in order to gain maximum benefit from it.

I increase the level of complexity in the examples and homework problems in a given course, and throughout the two quarter sequence. The following set of examples and problems in diffusion-reaction behavior illustrates the progression of complexity. Other sequences involve process control, fluid flow, and heterogeneous reactor theory. During the discussions of boundary value problems, the one-dimensional material balance equation for a porous catalyst pellet (slab, cylinder, or sphere) with a first-order reaction rate is developed and the significance of the effectiveness factor is outlined. The boundary value problem is solved by many techniques and the physical implications of the solutions discussed. The ensuing homework problem is the classical Weisz-Hicks problem [16], i.e., the material and energy balance equations for a porous catalyst pellet utilizing an exothermic first-order reaction. The solution of the isothermal example problem and the Weisz-Hicks problem (for various values of the Prater number, β) are shown in Fig. 1. I point out how the effectiveness factor can be greater than one for an exothermic reaction, and for increasing β , how multiple steady-states are obtained. The concept of diffusion and reaction is continued in the second course by considering the most common geometry used in practical application, namely, the finite cylinder with length equal to diameter. The material and energy balance equations now constitute a coupled set of nonlinear elliptic partial differential equations (symmetry in the theta direction is assumed). The solution of the elliptic problem allows the effectiveness factor to be calculated, and the results are compared to the following one-dimensional solutions: (a) in-

finite cylinder of radius equal to the finite cylinder, (b) infinite cylinder of equal volume to surface area (V/S) of the finite cylinder, and (c) sphere of equal (V/S) of the finite cylinder. Fig 2 shows the results. For all practical purposes, the one-dimensional models (b) and (c) predict the behavior of the finite cylinder. Model (c) gives nearly the exact behavior as the finite cylinder. Since the elliptic problem is more difficult to solve than model (c), it is pointed out that it is appropriate to use model (c) instead of the elliptic problem when modeling many heterogeneous reactors.

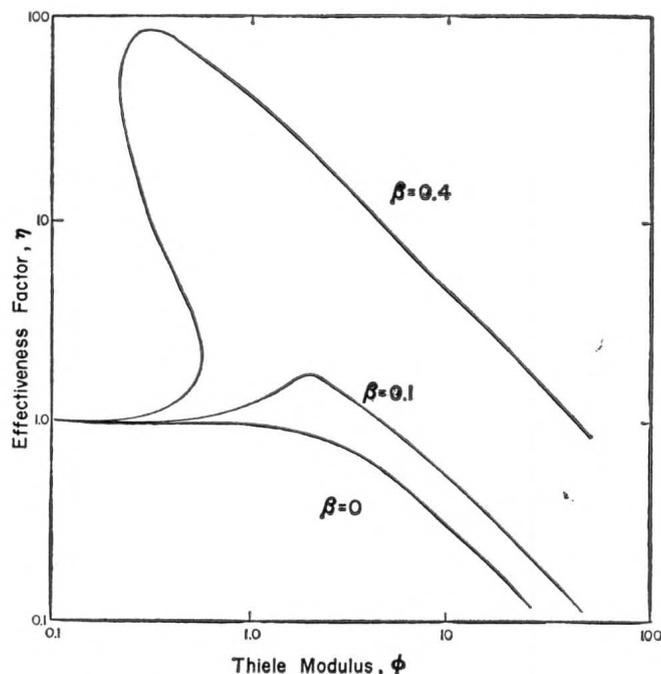


FIGURE 1. Effectiveness factor as a function of the Thiele modulus for a spherical catalyst pellet with first-order reaction.

WORK REQUIREMENTS

I assign one to two homework problems per topic and one design project per course. Homework problems are real chemical engineering problems with physical implications. Therefore, an equal emphasis is placed on the mathematics and the physics of the problem. A proper solution contains: (a) a detailed formulation of the physical situation into a relevant mathematical model, (b) the rationals for choosing the numerical technique and software package, (c) the numerical solution of the problem with a full error analysis and a comment or two on the performance of the software package, (d) an evaluation of the solution, i.e., does it make sense from a physical standpoint, and (e) the physical implications of the

solution. Each student works independently on homework problems, but for design projects, I allow groups as large as three to work together. The design projects consist of large chemical engineering problems. A typical design project would be to access the affects of disturbances in the feed to the feed-forward controlled distillation column shown in Fig. 3. This problem involves the solution of approximately forty initial value equations. Many of the design projects are constructed by the students and are used as part of their thesis research. A few projects have led to journal publications.

In conclusion, I have found that teaching numerical methods through the use of chemical engineering examples has kept interest levels high, and that the approach described in this article allows for maximal coverage and understanding. □

ACKNOWLEDGEMENTS

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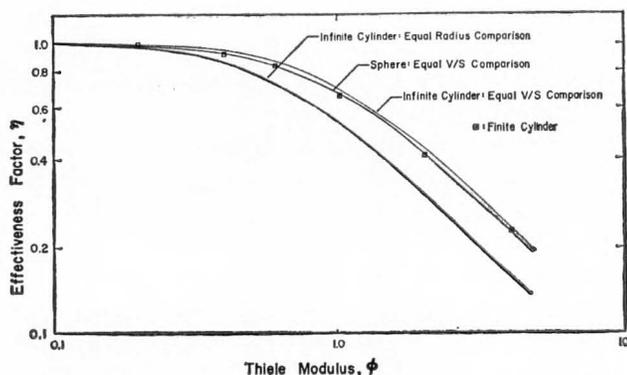


FIGURE 2. Effectiveness factor as a function of the Thiele modulus for isothermal pellets with first-order reaction.

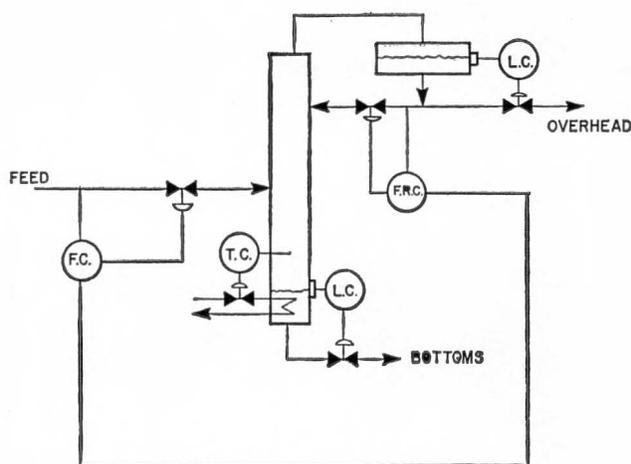


FIGURE 3. Feed-forward controlled distillation column. The column contains nine trays with the temperature control (T.C.) at tray 8, and the feed introduced on tray 6. F.C.: feed flow control, L.C.: liquid level control, F.R.C.: feed-forward control of the recycle from the measured feed flow rate.

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A Course on

PLASMA PROCESSING IN INTEGRATED CIRCUIT FABRICATION

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IN THIS PAPER WE review a course entitled "Plasma Processing in Integrated Circuit Fabrication" which was offered for the first time in the spring semester of 1983 at MIT. The course was taught jointly, listed both in chemical engineering and electrical engineering. It has been accepted as a permanent course which will be taught on alternate years.

Plasma processes are playing an ever expanding role in microelectronic fabrication, replacing many of the conventional wet etching and high temperature chemical vapor deposition processes. In very large scale integration (VLSI), plasma processes are required to provide fine spacial resolution and low temperature processing. In most of the plasma processes, the plasma is created by an electric field that accelerates electrons within the plasma. The electrons suffer collisions with gas molecules creating excited neutrals, free radicals, and ions. In this manner, energy is supplied to the plasma creating highly reactive species without significantly raising the average temperature of the gas. Microelectronic fabrication processes typically use low pressure plasmas (1-200 Pascals) which are weakly ionized (less than 10^{-4} mole fraction). They are more appropriately referred to as glow discharges rather than plasmas, due to the non-equilibrium between the electrons, ions, and neutrals from which they are composed. The first use of plasmas in integrated circuit fabrication was for sputtering processes which deposit or etch thin films. In a sputtering process, ions created within a plasma are accelerated by an electric field. Upon collision with the electrode, the ions remove or sputter material from the electrode by momentum ex-

The goal of this course is to teach the fundamental science of plasma processing as well as to give a brief overview of the present state of industrial processes.

change, etching the surface of the electrode. The sputtered electrode material can be deposited onto the surface of a wafer to form a thin film. By placing wafers on the sputtered electrode, a thin film on the wafer can be etched. A resist material placed selectively on top of the thin film is normally used to mask the ion bombardment inhibiting the etching in the selected areas. In the late 1960's, oxygen discharges were developed to produce atomic oxygen which chemically etches organic photoresist masks. Presently, plasma etching processes use a combination of sputtering and chemical reaction to remove with high resolution, thin films which have been masked with resist. Chemical vapor deposition is a process in which a gas is thermally decomposed at a hot surface to produce a thin solid film. For example, silane can be decomposed at a hot surface to deposit silicon. Plasma assisted chemical vapor deposition (PACVD) processes have been developed which use the highly reactive species created within a plasma to deposit thin films at lower temperatures than are possible with conventional chemical vapor deposition.

The goal of this course is to teach the fundamental science of plasma processing as well as to give a brief overview of the present state of industrial processes. This goal has a number of motivations. First, we perceive a general lack of understanding within the industrial community with regard to the basics of plasma physics and chemistry. Many of the present plasma process engineers treat plasmas as a "black art" which depends upon intuition and a great deal of trial-and-error. Most of the graduating students going into plasma processing have little or no training,

instruction, and/or experience in plasma processing. Also, the plasma physics courses most commonly taught deal with high density, equilibrium plasmas related to fusion reactors.

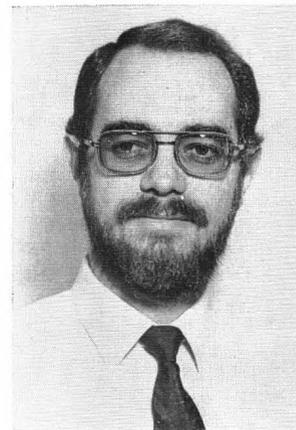
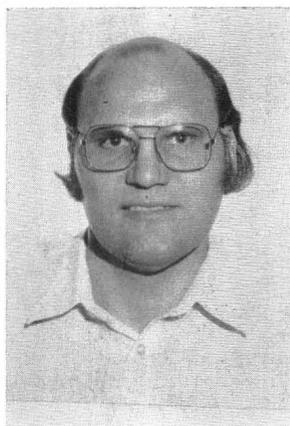
The present engineering state of the art is advancing extremely rapidly with the demands made by the microelectronics industry. We feel that by equipping the students with an understanding of the basics, they will be prepared to make the best use of the advancements. We also feel that an overview of the present use of the plasma processes along with the greater concentration on a few representative areas is best.

In deciding to teach a joint course between electrical and chemical engineering, the advantages and difficulties were carefully weighed. As faculty doing research in the area of integrated circuit fabrication, we have independently taught courses in the more general areas of micro-electronic processing in our respective departments. Although there is significant overlap in some of these courses, it is believed that the varied backgrounds of the students in chemical and electrical engineering as well as the different emphasis of the courses more than justified their mutual existence. We saw a need for a more advanced course dealing with the area of plasma processing, a new and rapidly advancing field. It was obvious that this field is highly interdisciplinary and that a pooling of our efforts would create a stronger course than either of us could teach alone. The benefit of having students with varied backgrounds was viewed as more of an asset to the class than a difficulty. The interaction between chemical engineering students who are mostly concerned with how a plasma process functions, and the electrical engineers who are much more aware of the uses of the structures and the subsequent requirements, was thought to be highly beneficial. We decided that a strong emphasis on the engineering science aspects of the processes would form a common background from which both groups would benefit.

As might be expected, no appropriate text could be found which covered all the material we desired. As a text, we chose *Glow Discharge Processes* by Chapman [1], as the most appropriate in its coverage. It is quite readable for the students and formed a basis upon which we built with papers from the literature. *Techniques and Applications of Plasma Chemistry* edited by Hollahan and Bell [2] was also very useful as a reference; in particular, Chapter 1 which deals with the

fundamentals of plasma physics and chemistry in glow discharges.

The class had an enrollment of 23 students during the bulk of the course, however, there were typically a number of additional students who sat in on the class depending upon the topic under discussion. Two of the students came from industry to attend the class. We required one homework set per week which accounted for 60 percent of the grade and a term paper which accounted for the remaining 40 per cent. As the term paper deadline approached, the class enrollment took an expected drop to 18 students. The remaining class consisted of 7 chemical engineers, 7 electrical engineers, 3 material scientists, and 1 physicist. We were quite pleased with the overall quality of the term papers and feel that the students benefited by being required to search the literature on the topic of their choice which dealt with plasma processing.



Herb Sawin was born in 1951. He received a Bachelors of Science in chemical engineering from Iowa State University in 1973 and his Ph.D. from the University of California (Berkeley) in 1980. His doctoral dissertation was on the catalytic decomposition of hydrazine using molecular beam scattering. In 1980 he joined the Massachusetts Institute of Technology where he is presently an assistant professor of chemical engineering. He is currently working on the plasma etching of silicon and silicides, the enhancement of surface reactions by ion bombardment, chemical vapor deposition of silicon, and fuel cells. (L)

Rafael Reif was born in Venezuela in 1950. He received the degree of Ingeniero Electrico from Universidad de Carabobo, Venezuela, in 1973, and the M.S. and Ph.D. degrees in electrical engineering from Stanford University in 1975 and 1979, respectively. In 1978 he became a Visiting Assistant Professor of electrical engineering at Stanford University, and in 1980 he joined the Massachusetts Institute of Technology, where he is presently an Associate Professor of electrical engineering. He is currently working on the Plasma Enhanced Chemical Vapor Deposition (PECVD) of crystalline silicon films, the PECVD of refractory metals and silicides, the computer simulation of CVD silicon epitaxy, and on low-temperature epitaxial and silicon-on-insulator technologies. (R)

We were quite pleased with the overall quality of the term papers and feel that the students benefited by being required to search the literature on the topic of their choice which dealt with plasma processing.

COURSE DESCRIPTION

The first one third of the course covered the basics of glow discharge physics and chemistry. Following the ultra-simplified model for gas kinetics presented in section 1.2 of *Molecular Theory of Gases and Liquids* by Hirschfelder, Curtis, and Bird [3], we quickly developed the gas phase kinetics and transport properties of a neutral gas. Chapman's coverage of this material in Chapters 1 and 2 was too weak in this area to give the student an appropriate physical understanding. Using Hollahan and Bell as a reference, the unique properties of a glow discharge caused by its weakly ionized nature were added to the

neutral gas kinetics. The prime emphasis was on the physics of the situation rather than the math and the derivation of the various energy distributions. The significance of the electron energy distribution and how it is related to both the plasma chemistry and the transport properties of the charged species was stressed. Chapters 3 to 5 of Chapman which cover the sheath kinetics, DC discharges, and RF discharges were taught in reasonable detail with some embellishment. We reviewed some of the main probes used to characterize plasmas used for microelectronic fabrication: Langmuir probes [4], optical emission [5], mass spectroscopy, and laser induced fluorescence [6].

Approximately one sixth of the course was spent on sputtering mechanisms and the sputtering processes [7] that have been developed for microelectronic fabrication. Chapter 6 of Chapman was used as background material and was heavily augmented. A very simplified model was used to generate the qualitatively correct results in lecture and in homework assignments. Topics

TABLE 1
Course Syllabus By Lectures

Gas Mechanics: Ideal gas law, energy distributions, mean free path, impingement flux	Sputter Deposition II: Etch rates, masks, profile control, ion beam vs. conventional, mask erosion, redeposition, angular dependence
Gas Kinetics I: Collision cross-sections, energy transfer, ionization, excitation, relaxation	Overview of Plasma Etching: definitions, wet vs. dry, uses, isotropic vs. anisotropic, selectivity
Gas Kinetics II: Completion of lectures	Etching Apparatus: Parallel plate, reactive ion etching, tunnel, reactive ion beam etching, costs, through-put, wet etch comparison
Electron Energy Distribution I: Plasma kinetic theory, transport phenomena	General Principles of Etching: Volatilization, additives, F and Cl etchants, flow, loading, example of a simple system (O ₂ etching of organics)
Plasma Chemistry: Plasma chemical reactions, reaction cross-sections, free radical reactions	Review of Si and SiO₂ etching
DC Glow Discharges: Glow architecture, secondary emission, cathode and anode glow	Aluminum Etching
RF Glow Discharges I: RF coupling, glow architecture, voltage distribution	Etching of Si₃N₄
RF Discharges II: Self-biasing, ion bombardment energies, electron energy distributions	Plasma Etch Control: Flowrate, power and bias, end-point detection
Sputtering Kinetics: Sputtering yields, mechanisms, chemical enhancement	Plasma Assisted Chemical Vapor Deposition: Overview, equipment considerations, commercial reactors
Optical Emission: Emission mechanisms, nomenclature, detectors	PACVD of Si₃N₄ and SiO₂
Laser Induced Fluorescence: Laser probes, mass spectro-analysis, quantification	PACVD of Amorphous Si
Other Plasma Probes: Langmuir probes, mass spectrometer, microwaves	PACVD of Poly- and Mono- crystalline Si and GaAs
Sputter Deposition I: Sputtering physics, DC and RF sputtering, ion beams, magnetron	PACVD of Refractory Metals and Silicides
	Plasma-Assisted Techniques: Oxidation, nitridation, annealing, ion beam deposition, ionized beam cluster deposition

discussed included DC sputtering, RF sputtering, contamination, bias sputtering, triode sputtering, magnetron sputtering, and ion beam technology. Sputtering processes which are capable of producing and controlling multicomponent films were also discussed.

The next one quarter of the class was spent in the discussion of plasma etching. Again, Chapter 7 of Chapman which deals with plasma etching was used as background material and was augmented. Dr. David R. Day, a research associate at MIT, assisted by teaching this section. First of all, the specifications and desirable attributes for good etching processes were outlined. Comparisons were made with wet etching processes that the plasma processes are replacing. Dr. Day chose to concentrate on the etching of carbonaceous materials such as photoresists and polyimides as an example system [8]. He developed an appreciation that etching proceeds by both a chemical reaction and physical sputtering as well as a strong interaction between them. He drew from the literature heavily; outlining the different types of reactors, the volatilization of materials, the use of gas mixtures, and loading in plasma etchers. Anisotropy of etching was discussed on a mechanistic as well as an engineering basis. An overview of some of the more industrially important etching systems was presented: silicon, silicon dioxide, aluminum alloys, silicon nitride, and refractory metal silicides. The aspects of safety, corrosion, and resist degradation were also discussed.

The remaining one quarter of the class was spent covering plasma assisted chemical vapor deposition. First thermally induced chemical vapor deposition was reviewed to build a basis on which the plasma assisted process could be appreciated. The modelling of thermal chemical vapor deposition was presented using classical boundary layer theory and surface kinetics. The need for plasma processes was brought out by reviewing the temperatures which are required for the thermal chemical vapor deposition and the desired deposition processes needed for VLSI. Case studies of silicon nitride, silicon dioxide, polycrystalline silicon, epitaxial silicon, refractory metal silicides, and gallium arsenide deposition processes were discussed.

Because our research work involves plasma processing, we were also able to enhance the class discussion with some of the difficulties we experienced such as pump oil contamination, RF interference, and impedance matching of the

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plasmas to the RF generators. The presence of a number of students who are presently doing research in the area kept the discussion lively. □

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A Course in

ADVANCED TOPICS IN HEAT AND MASS TRANSFER

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IT HAS BEEN ALMOST thirty years since the field of transport phenomena entered chemical engineering curricula. Essentially one excellent textbook has defined the scope of material usually treated in such courses; however, much of this material is now treated either as a requirement or as an elective in undergraduate programs. Since there is no obvious choice for a graduate level heat and mass transfer text specifically for chemical engineers, which would provide a framework for teaching such a course, it is left to the discretion of the instructor to construct an appropriate sequence of topics. What follows is a discussion of the type of material that has been covered in one such course. The goals of the course are to provide basic instruction in heat and mass transfer topics relevant to chemical engineering problems, and to train the students to develop mathematical descriptions of totally new situations which may be encountered in solving heat and mass transfer problems. Achieving the first goal is reasonably straightforward; the traditional method of lectures, reading, doing problem sets and taking examinations works reasonably well. Achieving the second goal is much more difficult but is, of course, the skill desired in research. The problems used for the second goal are either so different from assigned problems students are accustomed to, or are so deliberately vague, that students appear to get frustrated at not being certain whether or not they have the correct solution. Each problem set and each exam always has at least one problem requiring creativity rather than just routine analysis. Although there seems to be a latency period, by the end of the course most of the students appear to have improved their ability to handle new situations.

Table 1 is the course outline. The approximate times for coverage of the general topics in a



Joseph A. Shaeiwitz received his B.S. degree from the University of Delaware in 1974, and his M.S. and Ph.D. from Carnegie-Mellon University in 1976 and 1978, respectively. He has been on the faculty at the University of Illinois, Urbana, since 1978. Professor Shaeiwitz's research interests are in mass transfer, interfacial and colloidal phenomena. One major area has included several problems involving mass transfer of surfactants near interfaces including the dynamics of adsorption, micellar solubilization and emulsification. Related research focusing on solute diffusion in mixed micelle and microemulsion systems is also beginning. A second area involves multicomponent diffusion in solute-particle-solvent systems. This problem encompasses both modeling and experimental verification of enhanced particle capture efficiencies relevant to particle filtration in liquids.

fifteen week semester are shown in parenthesis and the numbers in square brackets refer to the reference list at the end of this paper. The details of the outline represent the total amount of material that has been covered all of the times the course has been given, and probably would require a four semester hour course to cover thoroughly. Indeed, it would not be difficult to devote an entire semester to each topic. Since the course is only offered for three semester hours, some of the material is either left out entirely, covered in less depth or used as problem set material. The latter option has the advantage of providing more flexibility in making up new problems, and gives the students opportunities to handle new situations independently. It is also obvious that no present text covers all of this

material; and, although it may be tempting to write one, it is also an integral part of the learning experience for students to familiarize themselves with the vast collection of literature on heat and mass transfer.

It is obvious from the outline that both heat and mass transfer are taught simultaneously. This method is preferred mainly because when I was in

school the topics were always covered sequentially, heat transfer and then mass transfer. This inevitably resulted in mass transfer being short-changed. The two topics may be covered in parallel if one is careful to point out when the analogy between heat and mass transfer fails. It is only necessary to point out that the analogy exists once; however, it is necessary to point out each

TABLE 1
Course Outline: Advanced Topics in Heat and Mass Transfer

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|---|--|
| <p>1. Review (one week)</p> <p>A. Shell Balances[6]</p> <ul style="list-style-type: none"> ● Simple cases ● Cases involving more complex math ● Boundary condition or source term? <p>B. Equations of Change [6]</p> <ul style="list-style-type: none"> ● Derivations for continuity, momentum and heat transfer <ul style="list-style-type: none"> ● Differential cube ● Divergence theorem ● Different types of fluxes ● A continuum entropy equation ● Macroscopic balances [6, 7] <p>2. Diffusive Transport (three weeks) [9, 10, 15, 19, 21]</p> <p>A. Steady</p> <ul style="list-style-type: none"> ● Slabs and membranes <ul style="list-style-type: none"> ● 1-dimensional ● Multidimensional <p>B. Unsteady</p> <ul style="list-style-type: none"> ● Solution methods <ul style="list-style-type: none"> ● Combined variable ● Laplace Transform ● Fourier Transform ● Separation of variables ● Duhamel's Theorem ● Physical considerations <ul style="list-style-type: none"> ● When to use a solution method ● Controlling resistances ● Short vs. long time solutions ● Intermediate regime <p>3. Simultaneous Heat and Mass Transfer (one week)</p> <p>A. Change of Phase Problems [9, 21]</p> <p>B. Fog Formation—An Interesting Example [31]</p> <p>C. Moving Boundary Problems in General [10, 12]</p> <p>4. Convective Transport (three weeks)</p> <p>A. Closed Channels [15, 17, 29]</p> <ul style="list-style-type: none"> ● Graetz problem <ul style="list-style-type: none"> ● Leveque solution ● Sturm-Liouville solutions ● Asymptotic behavior far from entrance ● Analogy to heat conduction <p>B. External Surfaces [15, 17, 18, 20, 26, 29]</p> <ul style="list-style-type: none"> ● Boundary layer theory <ul style="list-style-type: none"> ● Ordering arguments ● General solutions ● Important limiting cases ● Other approximate solution methods ● Integral methods | <p>C. Unsteady Convective Transport</p> <p>D. Turbulent Transport</p> <p>5. Interfacial Transport (one week)</p> <p>A. Resistances in Series</p> <p>B. Classical Theories</p> <p>C. Coupling between Navier-Stokes, Energy and Continuity Equations [4, 5, 30]</p> <p>D. Other Interface Models</p> <ul style="list-style-type: none"> ● Interface as a separate phase [4, 5] ● Forced diffusion [8] <p>6. Mass Transfer with Chemical Reaction (one week)</p> <p>A. Heterogeneous Reaction</p> <ul style="list-style-type: none"> ● Resistances in series ● Applications <p>B. Homogeneous Reaction [2, 13]</p> <ul style="list-style-type: none"> ● Rapid reaction ● Instantaneous reaction ● Interface models <p>7. Theory of Diffusion and Other Transport Processes (three weeks)</p> <p>A. Diffusivity Measurement Techniques [11]</p> <p>B. Diffusion vs. Sedimentation</p> <p>C. Irreversible Thermodynamics [14, 16]</p> <ul style="list-style-type: none"> ● Entropy production ● Coupled phenomena <p>D. Reacting and Interacting Systems [11]</p> <p>E. Electrostatically Coupled Systems [11]</p> <p>F. Multicomponent Diffusion [11]</p> <ul style="list-style-type: none"> ● Tracer, intra-, self and mutual diffusion [1] ● Solution of coupled equations <p>G. Multicomponent Mass Transfer [11]</p> <p>8. Carrier-Membranes (one week) [11]</p> <p>A. Physical Situation—an interesting example of multicomponent transport and mass transfer with chemical reaction</p> <p>B. Carrier Systems</p> <ul style="list-style-type: none"> ● Facilitated transport ● Co-transport ● Counter-transport <p>C. Irreversible Thermodynamics Formulation</p> <p>9. Particle Transport (one week)</p> <p>A. Failure of Continuum Theories—Need for Statistical Theories [3]</p> <p>B. Particle Adsorption—the intermolecular force boundary layer [23, 24]</p> <p>C. Particle Chromatography [24, 25, 28]</p> |
|---|--|

A problem on the time necessary to melt an ice cube (which, along with a few other problems, I confess are not original, but almost identical to ones assigned to me by Herb Toor when I was a graduate student) is used as either a lecture example, or as an assignment with result of each step given to guide the student through the problem.

time it fails. In all fairness, it is obvious from the outline that in this course, mass transfer is the major focus of attention, and I must confess that my personal research interests prejudice my allotment of time for each topic. A course emphasizing heat transfer might best be taught without the intrusion of mass transfer complications.

The semester starts with a review of shell balances, reference frames for mass transfer and equations of change, both differential and macroscopic, found in Bird, Stewart and Lightfoot [6]. It is assumed the class has already covered this material either somewhere in their undergraduate education or in our senior-graduate course which covers the entire book. The "sub-two" problems are all assigned as optional review problems, and many of the "sub-three" and "sub-four" problems are required. Three concepts are emphasized in this review. One is when a reaction or heat flux expression appears as a source term and when it appears is a boundary condition. Emphasis is made on analyzing each problem individually rather than using firm rules such as "homogeneous-source, heterogeneous-boundary condition." The standard porous catalyst problem as well as comparison of the one-dimensional rectangular fin problem to a two-dimensional version which allows conduction toward the main heat transfer surface amply illustrates this concept. Secondly, derivation of the equations of change is rarely done using the divergence theorem, owing to the popularity of the BSL treatment. This is emphasized along with the relationship between the differential and integral balances for an arbitrary control volume [7]. Finally, by assigning the circular fin heat transfer problem, the lesson is learned that while it may be straightforward to formulate many transport problems, one must be facile with many aspects of mathematics to obtain solutions. Memorization of Bessel equations or functions or other common functions, except for what to expect from what geometries, is discouraged; liberal use of mathematical handbooks is encouraged.

The first major topic covered is diffusive transport. Two major points are emphasized. These are developing the mathematical skills necessary to obtain solutions and obtaining a

physical understanding of the conduction process. Without care, the difficulty of the first goal can obscure the second goal. Even though solutions are tabulated for most, if not all, physical situations of interest [9, 10, 22], these books are written at a sufficiently high enough level that an understanding of the mathematics involved is required just to use them. Furthermore, obtaining the solution is part of the goal of teaching the students to handle new physical situations which may not have been anticipated by these authors. The usual partial differential equation solution techniques are introduced, as shown in the outline, and some insight into which method to choose for a particular situation is discussed. The narrow scope of the combined variable solution is demonstrated merely by changing from a constant temperature (or concentration) to a convective heat (or mass) transfer coefficient boundary condition. This introduces the Laplace Transform technique, but finite slab problems are found to be most easily solved using separation of variables and Fourier series. Being able to choose "the best" solution method upon examining a new problem is considered almost as important as obtaining the solution itself.

An intuitive understanding of conduction and diffusion is only possible if real numbers are plugged into the equations. The text by McAdams [19] is suggested as a possible alternative to Perry's [22] in finding heat transfer data, charts for quick calculations and correlations. A problem on the time necessary to melt an ice cube (which, along with a few other problems, I confess are not original, but almost identical to ones assigned to me by Herb Toor when I was a graduate student) is used as either a lecture example, or as an assignment with result of each step given to guide the student through the problem. This problem illustrates how, for a quick estimate, it does not matter whether some faces are horizontal or vertical since the free convection heat transfer coefficients only differ by 25%. For this problem, it is also found not to be necessary to use exact series solutions since the cube temperature does not differ in temperature by more than a few degrees from edge to center. The simpler external

control solution suffices for an estimate. Finally, since the numerical result for the melting time seems too long, the neglect of radiation is found to be serious. (This has been circumvented by a problem statement involving a large ice cube in an ice chest in the shade at a football game tailgate party, a situation of extreme practical significance.) Some appreciation of when a simpler solution will suffice in place of a more complex one is essential.

Simultaneous heat and mass transfer, which mostly involves change of phase problems, follows next. The mathematics is shown to be identical to conduction problems except for the extra boundary condition needed since the location of the phase boundary in the system at a given time is a new unknown. Physically, it must be appreciated that this is merely an energy balance at the moving boundary. Fog formation is an interesting example which illustrates the complexities of real problems as well as the simplifications that can be made in order to obtain quantitative trends [31]. Finally, the general treatment of moving boundary problems due to Danckwerts [10] is presented, and the students are left to decide for themselves whether they wish to use this method to solve problems, or to treat each new situation individually. I suggest the latter since problems of more recent interest such as injection molding of polymers were not anticipated in the general treatment. However, for simple one-dimensional problems, either method is considered satisfactory.

Quasi-steady state solutions are also covered. It is shown that for phase change problems involving very large latent heats, the position of the moving boundary with time is very quickly obtained by assuming a linear profile in the disappearing phase. This is usually a good time to introduce the frozen margarita problem; that is, how long will the liquid/solid slurry remain intact before the beverage becomes entirely liquid and, alas, an ordinary margarita. One possible solution (and not necessarily the best) method involves modeling the slurry as a composite of liquid and solid in series and estimating the melting time with a quasi-steady solution. This has the further advantage of demonstrating how the model for a physical situation need not involve the exact same geometry as the situation itself.

Deciding exactly what to cover in only a few weeks on the topic of convective transport is difficult. Topics considered to be of particular

interest to chemical engineers are chosen, since courses from other departments are available with appropriate biases. Hence, although heat transfer is considered, mass transfer applications are emphasized. The Graetz problem is covered first because solutions for the different regions parallel the different solution regimes for diffusive transport. The short-time error function solution for conduction involves almost identical physical assumptions as the Leveque solution for the entrance region. The series solutions used for longer transient time periods are just special cases of the more general Sturm-Liouville treatment necessary for longer distances from the entrance. Finally, the constant asymptotic Nusselt or Sherwood numbers far from the channel entrance directly parallel steady state conduction. The de-

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crease in Nusselt number with axial position is shown to directly parallel the decrease in the transient heat flux with time. This analogy makes understanding heat and mass transfer in closed channels relatively straightforward, as well as cementing the understanding of transient conduction.

The major topic covered pertaining to external surfaces is boundary layer theory. The concept is developed starting with fluid mechanics and then by moving into heat and mass transfer. Similarity solutions are developed for forced convection past a flat plate as well as free convection adjacent to a vertical surface. Extension to wedge flows provides a convenient problem assignment. Particular attention is focused on the large and small Prandtl number and the large Schmidt number solutions for arbitrary geometries [20]. (The small Schmidt number exists mathematically but there is no corresponding physical situation.) The latter solution is found to be extremely important since it encompasses diffusion in all liquid systems. The integral treatment of the boundary layer as well as other solution techniques are presented as examples.

The two topics covered under the heading of unsteady convective transport are presented mostly using examples such as Taylor dispersion and the dropping mercury electrode. Turbulent trans-

port is covered only to the extent of time averaging the equations of change, presenting some useful empiricisms and developing the analogy concept. Fortunately for this author, other courses at the university cover this topic in much more depth, and with much more personal insight by the instructor.

The major portion of the time allotted to interfacial transport involves changing the misconceptions about interfaces obtained by all students in their undergraduate mass transfer operations

The standard porous catalyst problem as well as comparison of the one-dimensional rectangular fin problem to a two-dimensional version which allows conduction toward the main heat transfer surface amply illustrates this concept.

courses. Therefore, after reviewing these treatments including the classical film, penetration and surface renewal theories, the concept of interfacial tension is introduced. The modified fluid mechanics boundary conditions at the interface are shown to correctly predict convective flows caused by concentration and temperature differences. Eventually the classical treatment of Sternling and Scriven [30] is presented in order to demonstrate the effect of interfacial convection on mass transfer. By then discussing other models of interfaces, interfacial transport becomes the first topic covered that is not totally well-defined and the progression of examples covered illustrate the development of research in a field.

Even though there are entire books on mass transfer with chemical reaction, only one, or perhaps two, weeks are devoted to the subject. First of all, diffusion in porous catalysts and resistances in series models of heterogeneous reactions are briefly reviewed since it is assumed that these topics are treated in depth in other courses. For mass transfer with homogeneous reaction, the film, penetration and surface renewal theories are discussed, emphasizing that the enhancement factors predicted by each theory do not differ significantly. Methods of treating instantaneous reactions, both irreversible and reversible, are presented—the former reinforcing the moving boundary problem techniques discussed earlier in the course and the latter laying the foundation for treating diffusion in reacting systems which follows later in the semester. This treatment suffices by providing a general understanding of

the topic without the drudgery of solving every possible variation in kinetics.

The next topic covered is the theory of diffusion and other transport processes. While it could be argued that this topic might well belong at the beginning of the course, the development of a more sophisticated approach to problem analysis and solution makes this topic much easier to treat later in the semester. The variety of methods available for measuring diffusivity are shown to sharply contrast the relative ease of measuring thermal conductivity. By examining the equilibrium between diffusion and sedimentation, the $1\ \mu\text{m}$ size is shown to separate brownian from non-brownian particles. Then the topic of irreversible thermodynamics is introduced, leading to such well-known phenomena as Fick's law, Fourier's law, Ohm's law, and coupled phenomena such as ultrafiltration, reverse osmosis, electrophoresis and multicomponent diffusion. Reacting systems such as weak acids and electrostatically coupled systems involving electrolytes provide relevant examples. While it is intuitive that a binary electrolyte may be uniquely represented by one diffusivity, and the irreversible thermodynamics formalism proves it, only combination of the diffusion equations yields the form for the effective diffusivity.

While the examples cited above manifest the concepts of multicomponent diffusion, numerous other examples are also discussed. Solution of the equations in Fickian form is found to be relatively straightforward as long as the diffusivity is assumed constant. The Stefan-Maxwell form is also introduced, and the advantages of each form are briefly discussed. Finally, the equations for multicomponent mass transfer are found to be a natural extension of those for multicomponent diffusion. The multicomponent solution is found to be particularly convenient since any physical situation for which a binary solution is available yields a multicomponent solution immediately. The assumption of constant diffusivity is pointed out to be serious theoretical limitation, but approximating the diffusivities at an average concentration is found to be an eminently practical solution.

At this point in the course, many topics of interest could be covered. The topic of carrier-membranes is chosen because it is a recent development and the subject of vigorous continuing research. It is also an excellent example of both mass transfer with chemical reaction and multicomponent mass transfer. Co-transport and

counter-transport are particularly interesting because they are examples of how one species can be transported continuously against its gradient as long as another species is "supplying the energy" by being transported down its own gradient. Occasionally, when other topics during the semester have been given more time, this topic has been handled by assigning the model development part of problem sets. This has the advantage of giving the students practice in handling a new situation, and progressively developing it to higher levels of complexity.

The final topic covered involves particle transport. This topic is favored mainly due to this instructor's research interests. The first lesson learned is that concentrated particle solutions do not form a continuum, and that statistical theories are necessary to describe the effect of particle-particle interactions on diffusion. This is done in a very general manner, since the level of statistical mechanics background varies widely between students. Particle adsorption represents an excellent example of extending well-known concepts to a new problem. The intermolecular force boundary layer used to model particle adsorption phenomena provides this lesson, as well as one on length scales. Since this boundary layer is often much smaller than the diffusion and hydrodynamic boundary layers, it is shown how macroscopically adsorption is described by adsorption-desorption rate constants, and how a microscopic analysis reveals a method for predicting these rate constants from knowledge of the specific interactions involved. Finally, particle chromatography provides an example of how hydrodynamic and colloidal interactions between particles and surfaces can be exploited for particle separations.

In summary, the course described represents one instructor's opinion on the material suitable for an advanced course in heat and mass transfer. In general, the breadth of material treated limits the depth of coverage of any particular topic. This, however, is totally consistent with the goal of training the students to be able to handle new situations. By treating a wide variety of topics, they have a convenient starting point on almost any problem that they might encounter. Since I believe that the ultimate goal of any graduate program should be to train problem solvers irrespective of research topic, the scope and purpose of this course is one part of achieving that lofty ideal. □

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CHEMICAL REACTOR DESIGN

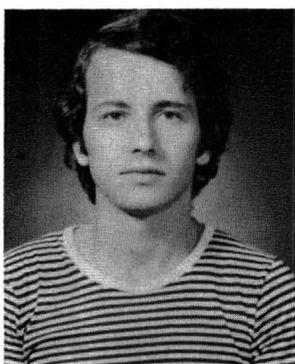
CHRISTOS G. TAKOUDIS

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A FIFTEEN WEEK COURSE in chemical reactor design was prepared to meet the needs of graduate students in Purdue's School of Chemical Engineering. Since this is essentially the only graduate course on chemical reaction engineering in our school, a variety of topics was included. The course outline is given in Table 1. The aim of the course is to bring together different disciplines on studying the behavior of chemical reactors. This behavior is intimately related to the interplay of chemical and physical rate processes.

There has been an increasing number of books on reaction engineering or analysis in recent times with widely varying directions or emphasis. In this course, the main text was Froment and Bischoff's "Chemical Reactor Analysis and Design" [1] and collateral reading was suggested from Lapidus and Amundson's "Chemical Reactor Theory, A Review." [2] Although these texts provided an organizational framework for this course, they were inadequate on several occasions. Hence, handouts were used and additional reading was suggested from numerous papers and other books, some of which are mentioned at the end. [3-11]



C. G. Takoudis received his Diploma (1977) at the National Technical University of Athens, Greece and his Ph.D. (1981) at the University of Minnesota in chemical engineering. He joined the faculty of Purdue University in November 1981. He has been involved in research in reaction engineering, heterogeneous catalysis and kinetics.

The aim of this course is to bring together different disciplines on studying the behavior of chemical reactors. This behavior is intimately related to the interplay of chemical and physical rate processes.

In order to maintain the pace shown in Table 1, some topics were not covered in depth. For these, several references were suggested and students' comprehension of these topics was examined through unannounced quizzes, homework problems, and midsemester exams. At the end of the course, the students were displeased with the main text, fairly positive to the recommended one, and pleased with the supplementary readings.

At the beginning of the course the students become familiar with the concept of stoichiometry and the implications of the law of mass action to the algebraic treatment of chemical reactions [3]. An introduction to the pure and applied aspects of kinetics of chemical processes as well as a unified treatment of the kinetic analysis of elementary steps, simple reactions and reaction networks form a review of the undergraduate chemical engineering kinetics course [4]. Special emphasis is given to chemisorption kinetics and equilibria, and to catalytic reaction kinetic models.

Despite the simplicity of a chemical reaction system or a reaction network, one may have to encounter questions like these [5]: Does a system admit a positive equilibrium? Can there be more than one positive equilibrium? Can the positive equilibria be unstable? Are there cyclic solutions? Although these questions are not simple, several existing theorems may provide useful information on the answers to the above. A series of examples from heterogeneous catalysis emphasizes clearly the advantages and particularly the limitations of the existing analyses.

Polymerization mechanisms and kinetics are covered next. Methods for the solution of the infinite set of difference-differential equations

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TABLE 1
Course Outline

<p>Stoichiometry. Elements of Reaction Kinetics. Chemical reaction. Rate of reaction The law of mass action Independence of reactions Measurement of quantity and its change due to reaction Invariants of a system of reactions</p> <p>Homogeneous and Heterogeneous Reactions Intrinsic reaction rate Chemical kinetics of elementary steps The steady-state approximation The rate determining step Ambiguity of simplified kinetics Chemisorption in kinetics and equilibria Some illustrations of catalytic rate models and mechanisms</p> <p>Mathematical Aspects of Mass Action Kinetics Mechanisms, kinetics and equilibria The stability of open isothermal reactors with complex chemistry Reaction network structure Multiple equilibria and chemical oscillations Advantages and limitations of the "zero deficiency theorem" and other related theorems Applications from heterogeneous catalysis</p> <p>Polymerization. Biochemical and Fermentation Kinetics Polymerization mechanisms and kinetics Microbial kinetics and dynamics Growth of a single population Growth of mixed populations</p> <p>Lumped Kinetics. Parameter Estimation Lumping analysis in monomolecular reaction systems Structure of a lumpable monomolecular system for reversible chemical reactions Kinetic behavior of a network of first order reversible reactions New methods of parameter estimation in linear systems Parameter estimation in non-linear systems</p> <p>Conservation Equations for Chemically Reacting Multicomponent Mixtures in Continuous Media The continuity equations The energy equation The momentum equation Equation for a retreating surface</p> <p>Catalytic Heterogeneous Reactions. Single Particle Studies The general equations of diffusion and reaction Effectiveness factor The single reaction in an isothermal pellet Reaction in a slab The first order reaction The infinite cylinder. The sphere Finite and hollow cylinders The reversible first-order reaction Reaction with volume change The pth-order reaction Langmuir-Hinshelwood kinetics The single reaction in a non-isothermal body The equations and methods of solutions The first order reaction. Boundary conditions General kinetics Multiple reactions</p>	<p>Lumped resistance models Uniqueness and multiplicity criteria</p> <p>Stability of the Steady State and Dynamic Behavior Tests for stability. Limit cycles Stability and dynamics of lumped resistance models Some features of the transient behavior of diffusing and reacting systems Numerical methods</p> <p>Catalyst Deactivation Types of catalyst deactivation Kinetics of catalyst poisoning Kinetics of catalyst deactivation by coking Separability of catalytic deactivation kinetics</p> <p>Non-catalytic Reactions Solid-fluid reactions Gas-liquid reactions</p> <p>The Batch Reactor The isothermal and non-isothermal batch reactor Optimal operation policies and control strategies</p> <p>The Continuously Stirred Tank Reactor The basic mass and energy balances The design of a single reactor The stability and control of the steady state Sequences of stirred reactors Transient behavior</p> <p>The Tubular Reactor Types of tubular reactor The mass, momentum and energy balances Design principles. Optimal design The effects of flow profile Axial dispersion in tubular reactors Criteria for the uniqueness of the steady state Stability and transient behavior</p> <p>The Fixed Bed Reactor Factors in the design of fixed bed reactors Modelling of fixed bed reactors Pseudo-homogeneous models. Heterogeneous models Fixed bed reactors with heat exchangers Stability and transient behavior</p> <p>Nonideal Continuous Flow Reactors Age-distribution functions Application of age-distribution functions Flow models</p> <p>The Fluidized Bed Reactor The two-phase theory. Fluid mechanics of bubbles Two-phase theory applied to catalytic reactors Division of gas flow, bed expansion, and phase volumes Factors in the design of fluidized bed reactors Stability and multiplicity of the steady state</p> <p>Multiphase Flow Reactors Types of multiphase flow reactors Trickle bed reactors Design principles Wetting efficiency Interphase mass transfer. Heat transport Pressure drop and liquid hold-up Reactor models</p> <p>Optimization of Chemical Reactors Conventional and unconventional optimization Globally optimal design.</p>
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pertinent to polymeric systems, and step and chain growth polymerizations are discussed in detail. Unstructured and structured models of microbial kinetics are a precursor to the understanding of the growth of mixed populations, and microbial dynamics is a precursor to the stability of a steady state.

The importance of lumping in the petrochemical industry is presented and lumping analysis in monomolecular reaction systems is discussed [6]. Also, parameter estimation and kinetic models based on experimental data are increasingly used in the chemical industry for the design of catalytic reactors. Hence, parameter estimation and kinetic behavior of a network of first order reversible reactions or non-linear reaction systems are discussed in depth.

Since the investigation of chemical reactors involves a synthesis of information pertaining to the chemical reacting system such as thermodynamics (e.g. heat of reactions, equilibrium compositions), kinetics (reaction rate expressions) and those relating to pertinent physical rate processes (momentum, heat and mass transfer), conservation equations for chemically reacting mixtures are discussed next. The conservation of mass, momentum and energy appended by appropriate phenomenological descriptions of physical laws (e.g. Fourier's law of heat conduction) and economic considerations govern the rules of this synthesis.

After a reference to the general equations of diffusion and reaction, single particle studies follow [7]. Different particle shapes, various kinetics, isothermal or nonisothermal operation and single or multiple reactions in permeable catalysts are discussed in detail. Special emphasis is given to boundary conditions and asymptotic behaviors. Also, at this point, the students become familiar with the concept of lumped resistance models and the possible serious pitfalls of such a lumping.

Once the above investigation of diffusion and reaction in permeable catalysts is completed, the following questions may arise [8]: Which steady states can be realized? What initial conditions may lead to a given steady state? Could periodic operation result? Answers to these questions are presented in two stages. First, after a quick review of the autonomous ordinary differential equations and the tests for stability, the stability and dynamics of lumped resistance models are discussed in depth. Second, several features of the transient

behavior of distributed systems are investigated with emphasis on diffusing and reacting systems.

After a review of the different types of catalyst deactivation, the kinetics of catalyst poisoning and of deactivation by coking are discussed. Emphasis is given to the separability of catalytic deactivation kinetics and to the implications of catalyst deactivation in a number of chemical processes.

Solid-fluid and gas-liquid non-catalytic reactions are covered in depth next. The shrinking core model, the grain model, and the pore model with structure are investigated within the framework of the solid-fluid reactions.

A unified treatment of chemical reactor analysis and design is complicated by at least two sources of divergent behavior. Naturally, the diversity of chemically reacting systems would be inherited by the reactors in which reactions are carried out. Furthermore, reaction equipment itself covers a wide variety such as stirred tank, moving bed, packed bed, fluidized bed and other types of reactors in which the relative role of physical and chemical rate processes may be profoundly different. Therefore, it should be evident that general results on reactor behavior or design prescriptions are not to be found. However, the divergent features of chemical reactor analysis have been presented in a proper perspective in [9].

The batch reactor is investigated under isothermal and nonisothermal operation. Special attention is given to optimal operation policies and control strategies.

The continuously stirred tank reactor (CSTR) is covered next. The design principles of a single or a sequence of stirred reactors are discussed in detail. After a review of the stability of the steady state and the transient behavior of a CSTR, the optimal sequence of stirred reactors based on the principle of optimality is presented.

The investigation of the tubular reactor comprises design principles, the effects of flow profile and axial dispersion. Emphasis is given to the comparisons and connections between a CSTR and a plug flow reactor. Criteria for the uniqueness of the steady state and a discussion on the stability and dynamic behavior of a tubular reactor conclude the analysis of this type of reactor.

The fixed bed reactor is investigated next. The factors in the design of fixed beds are discussed in detail. Pseudo-homogeneous and heterogeneous models are presented. Special attention is given to runaway phenomena, excessive sensitivity to variations in some parameters, and the non-steady

behavior due to catalyst deactivation. The current state of art on multiplicity, stability and transient behavior of a fixed bed reactor is also discussed.

After a brief review of imperfect mixing in reactors and age-distribution functions, the analysis and design of the fluidized bed reactor follows. The design principles of such a reactor are discussed in detail within the context of the two-phase theory applied to catalytic reactors. Several reactor models are discussed with emphasis on the assumptions and approximations of each one of them. The analysis of a fluidized bed becomes complete with a discussion of desulfurization with limestone in a fluidized coal combustor.

The trickle bed reactor is investigated next [10]. Emphasis is given to internal and external wetting efficiencies, mass transfer pertinent to trickle flow, and the factors in the design of such a reactor.

An overview of conventional and particularly unconventional optimization concludes this course. Special emphasis is given to globally optimal design [11].

The last stage of this course is a take home final exam. This exam includes a set of data of the methanol synthesis from H_2 and CO (in the presence or absence of CO_2). This is a simple system chemically, the thermodynamic properties of the chemical species are well-known, it has commercial significance, and it is not too simple kinetically. The students have to develop a kinetic model for the synthesis of methanol from that set of rate data; to simulate specified plant-scale catalytic reactors at specified reaction conditions, using their kinetic model; and to summarize their results. They are given the types of reactors, the reaction conditions and most thermodynamic and physical property data. The reactors may be fixed or fluidized beds, one- or two-dimensional, and isothermal or nonisothermal. The purpose of this project is to compare the kinetic models and simulated reactor performance calculations generated by various students working independently from a common data base and set of assumptions. The modeling process itself—by incorporating different interpretations of experimental data into the basic kinetic models—can influence the final reactor design and its ultimate performance dramatically.

Student evaluation of this course has been favorable and their comments indicate that they enjoyed the final project. □

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ChE letters

DEAD STATE NOT A DEAD ISSUE

Dear Sir:

Re: Availability (Exergy) Analysis, and Environmental Reference States (*CEE*, p. 138, Summer 1983)

Nothing pleases an author more than a long and careful review, seasoned with salutary adjectives, of his book [1]. Consequently I am obliged to both the reviewer and the editor for their generosity.

Permit me use of this letter to try to put to rest an issue raised in the review—the proper environmental reference state to be used for availability calculations.

Almost any reference state will do; as long as it can be explicitly defined, is convenient, is used consistently, and is clearly stated to readers and users whenever absolute rather than incremental availability changes are presented.

I have chosen the same reference state used throughout the chemical literature for "Standard Enthalpies of Combustion"—and hence I call the availability values compiled in my book "Standard

Continued on page 197.

A Course in

PROJECT EVALUATION IN THE CHEMICAL PROCESS INDUSTRIES

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THERE APPEARS TO BE a difference in perception between teachers of chemical engineering and the industry which employs their students—a perceptual difference as to what constitutes a balanced course of instruction that best prepares the students for their industrial tasks. There is a point of view in some industrial quarters that chemical engineering education is too “theoretical” (whatever that may mean) and that students enter industry unprepared for the realities of the business world. There is an academic point of view that maintains that the task of the university is to *educate* the student in the fundamental sciences (and, at the graduate level, to teach research skills in those sciences), for it is versatility in the fundamentals that allows the chemical engineer in industry to be creative and effective in a gamut of endeavors, to be a *general problem solver*. The latter point of view maintains that it is industry’s own responsibility to indoctrinate its employees so they may function well in the world of applied technology and business.

There is a great deal to be said for both points of view. There is no question that chemical engineers, by virtue of their exposure to the unique combination of fundamental sciences which constitutes the chemical engineering curriculum, have gained the reputation of exceptional problem solving ability in all industrial functions. Yet the academic world has not ignored industry’s call for educational realism, and university chemical

The purpose of the course is to expose the neophyte chemical engineer to the methodology used in the chemical process industries to evaluate the ultimate commercial feasibility of proposed new projects.

engineering curricula continue to exhibit a growing industrial cant, as evidenced by many articles in this journal. Most corporations in the chemical process industries profess to be moving in the direction of specialized, small-volume, high-priced products; this trend, if true, will demand of the universities, more than ever, an education which blends a strong background in the fundamental sciences with some nurturing of skills that will allow the neophyte engineer to handle the anticipated heavier demands of project management and evaluation.

At the University of California, Berkeley, the tradition of an industrial input into the chemical engineering curriculum goes back almost three decades, to the organization of an undergraduate process design course by practicing engineers in industry—Charles F. Oldershaw (Dow Chemical Co.) and later E. Morse (“Bud”) Blue (Chevron Research Co.). The participation of part-time instructors from industry has since been extended to the graduate curriculum as well; moreover, an industrial process design and development option is available to students working toward the PhD degree. The department is served by an Industrial Advisory Board whose members are top corporate managers from several companies; many of the industrially-oriented programs were initiated upon their recommendation.

Indeed, some ten years ago the board suggested that an advanced project evaluation course be incorporated into the graduate curriculum. On the strength of my industrial experience, I was asked by Jud King, at that time department chairman, to organize and teach such a course. I confess that I accepted this challenge with a certain degree of reluctance, for I had quite enough to keep myself usefully occupied at The Dow Chemical Co. Nevertheless, I took the plunge, and it seems to me that all concerned—my industrial employer, my departmental colleagues, the students, and certainly myself—have benefitted from the resulting exchange of information, ideas, and points of view.

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J. Frank Valle-Riestra received a BAS degree in mechanical engineering from the University of California, Berkeley (1944), and a BS degree in applied chemistry (1948) and an MS degree in chemical engineering (1949) from the California Institute of Technology. He has been employed by The Dow Chemical Co. since 1949 and currently holds the title of Senior Associate Scientist. His duties include organization and management of a process development group in Dow's Western Division Applied Science Laboratories in Pittsburg, California. He has held a post of Lecturer in the Chemical Engineering Department, University of California, Berkeley, since 1975. Included among his publications is a recent book, "Project Evaluation in the Chemical Process Industries," published by McGraw-Hill Book Co.

COURSE OBJECTIVES

The purpose of the course is to expose the neophyte chemical engineer to the methodology used in the chemical process industries to evaluate the ultimate commercial feasibility of proposed new projects. It is an attempt to give some insight into the intricacies of industrial project management.

As such, the course goes beyond the subject matter of allied courses previously described in this journal—doctoral level engineering economics (Oran L. Culberson, Fall 1979), or the structure of the chemical process industries (T. W. F. Russell, Fall 1979)—although elements of each are, indeed, to be found. Economic principles which may already be familiar to many students are reviewed, and elements and analytical tools that are new are introduced—the economic, marketing, and managerial techniques commonplace in industry. The principal thrust is to impart skills in the *integration of previously acquired disciplines* to facilitate preliminary process synthesis, to help gain an appreciation for the nature of industrial projects and the industrial viewpoint used in managing them, to become adept at creating a successful business venture. The ultimate objective is to give the neophyte chemical engineer

the background for the assumption of project managerial responsibilities at the earliest stages of an industrial career.

COURSE STRUCTURE AND CONTENT

The course is listed in the catalog as "Chemical Engineering Economics and Project Evaluation"; it is a three-unit course given once a year. (It will be maintained as a three-unit course following conversion this year from the quarter to the semester system at Berkeley.) A senior process design course is prerequisite; most participating students have been graduates, but undergraduates taking process design concurrently have performed quite well.

The subject matter is presented as six sequential concepts:

1. **The Industrial Environment.** The nature of the industrial workplace wherein project evaluation is practiced is described, and the job functions of the professional chemical engineer are placed in context.

2. **The Mathematics of Finance.** The mathematical tools of project evaluation are presented, but concepts rather than manipulative skills are emphasized. The concept of the time value of money, which permeates the subsequent course material, is introduced.

3. **The Evaluation Process.** This is the core material of the course and includes project definition, investment analysis, net revenue analysis, project economic analysis, and evaluation of criteria of economic performance—the various subjects tied together as shown in Fig. 1.

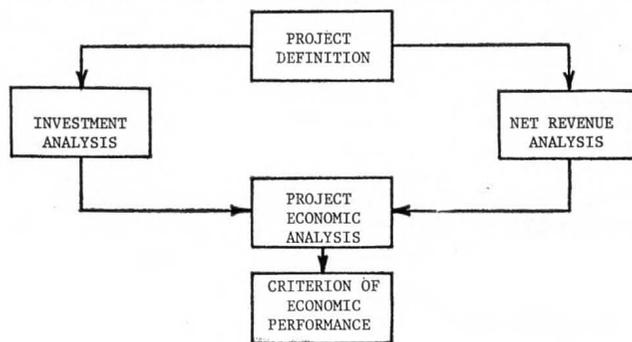


FIGURE 1

4. **The Analysis of Alternatives.** The core material is generalized for the case of "multicomponent" systems.

5. **Management of the Developing Project.** Management techniques for the advancement of projects from the laboratory to operating commercial units are introduced; these include techniques of construction time and cost control.

6. **Performance Analysis of the Corporation.** The corporation is evaluated as an ensemble of individual projects, and the performance is gauged in terms of criteria prescribed for the separate projects.

Within the context of this sequence a variety of special topics is introduced, all of which impact

peripherally upon the core material and are intended to stimulate the interest of the student. The discussion of the industrial environment incorporates an overview of many aspects of the chemical engineer's work—the gamut of human relations problems; challenges of professional development; the technical-managerial dichotomy; a realistic approach to the problems of ethics. The engineer's responsibilities for environmental protection and product stewardship are repeatedly emphasized, from the point of view of ethics and good citizenship as well as the point of view of assuring the continued productive functioning of the chemical industry in a distrustful society. Project definition, the first step in the evaluation sequence, in-

. . . the academic world has not ignored industry's call for educational realism, and university chemical engineering curricula continue to exhibit a growing industrial cant.

cludes an introduction to marketing research and the methods of projecting demand and an acceptable pricing structure—subjects frequently entirely novel to students.

Chemical engineers are fond of systematization and mathematical analysis, and these preferences are recognized by introducing aspects of risk analysis—decision trees, Monte Carlo methods for projecting the probability distribution of criteria of economic performance, life cycle theory, construction of sensitivity diagrams, and others. Both strengths and weaknesses of risk analysis are emphasized. Several aspects of network analysis are presented, in particular CPM and PERT techniques used in project planning. Methods of linear programming are applied to the problem of the allocation of resources. A unique approach is outlined for the calculation of the inflation-adjusted, after-tax rate of return upon the average corporate project investment from data in annual reports.

TEACHING STRATEGY

Problem solving receives heavy emphasis in the course. Assigned problems not only illustrate but also expand and supplement lecture material and reading assignments. The problems are often open-ended and unstructured; students are given a wide-ranging indoctrination into methods of attacking such problems and are taught the techniques of problem *synthesis*, in contrast to the analytical approach common to most of their previous courses. Most of the problems require the

application of knowledge acquired in the course of a typical undergraduate chemical engineering curriculum. The purpose is to force students to utilize the sum total of their acquired engineering know-how, to reach back and to apply facts and techniques not necessarily contained in lecture material. This is a source of irritation and unhappiness to some students, but it is typical of the problems that actually confront the engineer in industry.

The fact of the matter is that students *like* to solve problems, and the review of solutions and the accompanying commentary take up a considerable portion of class time. Students also enjoy group participation in the solution of experiential exercises and other enrichment activities to supplement lecture material. My lecture notes have been expanded into a book, "Project Evaluation in the Chemical Process Industries", published this year by McGraw-Hill Book Company. I anticipate that use of the text, with supplemental reading assignments, will leave more class time for enrichment activities and anecdotal accounts of industrial experiences.

TERM PROJECT

Short (one-hour) examinations constitute a standard evaluation technique of acquired skills in specific course areas. However, a massive final examination has not appeared to me to fill a useful course overview role. In order to demonstrate skills in project evaluation, one ought to evaluate a project, and this, in fact, constitutes the substance of a term project assignment. Four-person teams are asked to investigate the commercial feasibility of building a new production facility in a specific geographical area to manufacture a specific product. The team starts with a common scenario describing an existing integrated corporate complex, and an additional scenario is given which outlines an assigned business proposal in general terms. The team is asked to write a report to the corporation's management summing up and documenting its recommendations. Team members are asked, on a prearranged basis, to visit industrial libraries to consult business publications not normally available in university libraries.

A typical proposal might involve the construction of a hydrogen peroxide plant in the San Francisco Bay area to serve the West Coast pulp and paper industry, or the investigation of prospects for gasohol, obtained from cottonseed hulls, in the Gulf Coast area. The scenario given

to each team must be carefully designed to keep the investigation within reasonable limits. The final report gives students much-needed writing practice and serves as a vehicle for teaching content and style that corporate management likes to see in a business overview report. Students invariably approach the project with a great deal of enthusiasm, for they quickly recognize the challenge of a "real world" situation. I must say that the results have been a joy to me—topnotch professional-grade business analyses.

Occasionally student teams have chosen to concentrate on term projects of their own choosing, not necessarily involved with production planning—perhaps a study of the feasibility of aeolian power, or research into novel economic analyses such as process step scoring. Individual projects have been assigned to those who, for some reason, cannot participate in a team effort. Assignments have spanned such widely diverse subjects as life cycle theory, optimum surge tank policy, and the economics of reclamation of paper from garbage.

ENRICHMENT TECHNIQUES

Term projects and other enrichment activities do require effective instructor-student contacts outside of classroom hours. A few of the more important classroom enrichment techniques have included the following:

Oral Presentations. Students are asked to do library research on specially assigned subjects and to give a ten-minute presentation in class. The purpose is to give students some badly needed practice in technical speaking and to give them some feel for the nature of time-restricted, industrial oral presentations. Typical assigned subjects have included:

The Delphi method.

Status of engineering registration in state.

ASPEN, use in economic evaluation.

Geothermal power: status and costs.

The presentations have not proved to be very popular with students, most of whom just do not like to speak in front of their colleagues. Nevertheless, I consider the speaking experience to be beneficial.

Résumés. A first assignment in the course has been the assembly (or update) of the student's résumé. The instructor writes out an individual critique on each résumé submitted; this is followed by office consultation when requested. After-class seminars on job interview techniques have been well attended.

Term Project Reviews. A worthy review technique involves a small group of volunteer engineers from industry who interact directly with the project team by offering a report critique and exploring alternative project aspects. Such interaction has been warmly received by both groups of participants.

Visiting Lecturers. A welcome break in class routine

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is to have visiting lecturers talk about special subjects such as the evaluation of securities.

Special Projects. Projects involving participation by all members of a class have been tried. One such project involves contacting of equipment vendors by individual students to get recommendations and quotations on purchase inquiries for specially formulated "pretend" applications. The exercise gives students the experience of such vendor contacts and a great deal of useful technical information. Most vendors have been eminently cooperative in this venture.

EVALUATION

Students are fascinated and excited by the opportunities the course offers—a glimpse into the "industrial real world", an opportunity to sharpen the skills which that world demands. Even students with some industrial background welcome the chance to integrate their haphazard experiences into a systematized project-evaluation discipline. End-of-the-course written evaluations have been gratifyingly favorable.

The adoption of a course of this kind into the graduate curriculum is an important step in preparing students of chemical engineering for the assumption of project-management duties which form such a paramount part of their industrial careers. □

A Course on

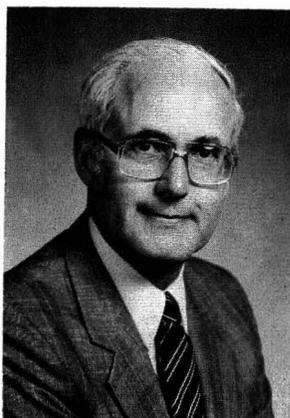
SURFACE PHENOMENA

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COLLOID AND SURFACE SCIENCE have been subjects of interest to scientists for many years. Within the last 20 years engineers have been paying more and more attention to this area of study. The more recent developments of the application of mathematical modelling and the gradual collection of numerical values for different surface properties have meant that colloid and surface science can be used to solve industrial problems. The combination of the fundamentals of surface phenomena with practical problems is what is unique about the graduate course offered in our department. The course is structured around a series of case problems encountered in the process illustrated in the flow diagram shown in Fig. 1. Here the engineer is faced with a multi-phase reactor, a phase separator, a vacuum distillation column, a solvent extraction process, a wastewater treatment facility and a coating process.



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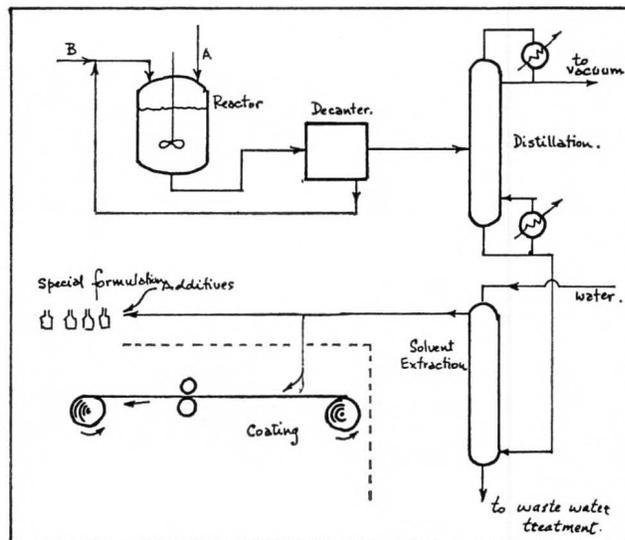


FIGURE 1. An imaginary process.

The course is divided into nine units and in each of the nine units students focus first on a case problem related to the process shown in Fig. 1 that is to be solved. The problems have been chosen carefully so as to require certain new knowledge in the area of surface phenomena. Once this knowledge has been acquired the practical calculations are then completed to solve particular case problems. Each unit ends by discussing other applications of the fundamental concepts of surface phenomena to practical problems of interest.

The first unit focusses more on what is a surface and a way of thinking about surfaces that forms the background for the rest of the text. The very thin thickness of the surface, the anisotropy of the surface and the force fields that a molecule experiences in the surface are the major themes in the first chapter. The basic idea that two-dimensional surface phenomena is but an extension of the familiar three-dimensional behaviour is the overall theme of the course. The identification of analogous two-dimensional surface properties to the familiar three dimensional

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surface properties is highlighted. These are illustrated in Table 1. Similarly, the analogous surface equations of change are tabulated and contrasted with their three dimensional bulk phase analogues. Practical problems are given to illustrate the application of these principles.

The next unit helps the student identify when surfaces should be important. Although much of the detail in this unit focusses on particle and polymer size characterization, the emphasis is on thinking about when surface phenomena will become important. The general guidelines are whenever the particles are less than a millimeter in diameter, whenever we encounter thin films, whenever a surface is broken to create sprays, emulsions or powders, whenever surfaces are bound together, whenever reactions occur at surfaces, and whenever we experience some unexplained behaviour.

The third unit focusses on the multiphase reactor and poses the question "How does one decide on the operating conditions within the reactor to generate a dispersion with a given characteristic size?" More specifically, "For the reactor in our process, the vessel is 2 m in diameter with a 0.7 m diameter, 6 bladed impeller. Full baffles are used. If the reactant mixture in our alkylation reactor is i-butane and 98% sulfuric acid, what should be the rotational speed of the impeller to give a volume to surface average drop size of 200 μm ? Assume the temperature is 20°C and that the holdup is 0.40." Since this problem involves the creation of an emulsion, surface phenomena should be important. To answer this question requires that we learn something about surface tension. The concept of a surface tension of a liquid is discussed as a thermodynamic reversible work required to increase the surface area by one unit, as a two-dimensional pressure in a mechanical energy balance and as the result of cutting the microscale bonds to create a surface. Methods of estimating the dispersion contribution of surface tension are given. Tables of data are provided. Measurement techniques are surveyed. Methods of estimating both the surface and interfacial tensions for fluids systems are given. The fundamental concepts introduced are:

a. Young-LaPlace equilibrium relationship between bulk phase pressures and surface tension:

For a single surface surface

$$p^{\text{II}} - p^{\text{I}} = \gamma \left[\frac{1}{r_1} + \frac{1}{r_2} \right]$$

TABLE 1
Analogous Properties in Bulk and Surface Phases

Concept	Bulk Phase	Surface Phase	
		Parallel to Surface	Perpendicular to Surface
Temperature	T	T ^o	
Pressure	P	γ , surface tension π , surface pressure	
Concentration	c	c ^o , surface concn. Γ , surface excess concentration	
Shape	NA	radii of curvature	
Chemical potential	u	u ^o	
Electrochemical potential	e	e ^o	
Charge	σ	σ^o	
Potential	ϕ	$\phi_{DL}^o X$	
Internal Energy	U	U ^o	
Entropy	S	S ^o	
Enthalpy	H	H ^o	
Gibbs Free Energy	G	G ^o	
Helmholtz Free Energy	A	A ^o	
Work functions		of cohesion of adhesion	
Force balance		θ , contact angle S, spreading coefft.	
Thermal conductivity	k	k ^o	k*
Electrical conductivity	K	K ^o	K*
Diffusivity	D	D ^o	D*
Elasticity, shear coefft.	G	G ^o	
dilational coefft.	ϵ	ϵ^o	
Viscosity, shear coefft.	μ	μ^o	
dilational coefft.	K	K ^{o*}	

b. For fluids whose intermolecular forces are based solely on physical forces (and no hydrogen bonding occurs), then

$$\gamma^d = \frac{1 A}{4(6 \pi h_0^2)}$$

or for close separations,

$$\gamma = \frac{1.2 A}{4 \pi y_0^2}$$

c. For two liquids

$$\gamma_{\text{II-III}} = \gamma_{\text{I-II}} + \gamma_{\text{I-III}} - 2\phi\sqrt{\gamma_{\text{III}} \gamma_{\text{II}}}$$

where

p = pressure

γ = surface tension

r = radius of curvature

A = Hamaker's constant

h = distance of separation between two layers

y = distance of separation between molecules

ϕ = Good and Elbing correction factor

Super- or subscripts

I = bulk phase I

II = bulk phase II

III = bulk phase III

d = dispersion component

The combination of the fundamentals of surface phenomena with practical problems is what is unique about the graduate course offered . . . it is structured around a series of case problems . . .

With this background in surface phenomena, the students then proceed to select the speed of rotation for the case problem: 2.4 rps. From this practical calculation the students then estimate what happens to the drop size distribution if the reacting mixture is discharged from the reactor at 5 m per s through an 8 cm diameter pipe. The answer to this is that the volume to surface average diameter decreases to 195 μm . Other variations on the theme would be to predict the drop size distribution coming from a pump that is pumping the material. These basic principles that have defined surface tension illustrate how the dispersion is now extended to other applications. These include bubble formation as required in an activated sludge reactor, flotation or liquid phase oxidation reactors; the diameter of sprays for drying in spray dryers, air pollution control equipment, jet scrubbers, ink jet printing and sprays of insecticides. All of these applications have considered only fluid-fluid surfaces. We add the definition of surface tension for solid systems at this stage and go on to illustrate how this information can be used to describe crushing and grinding circuits.

The case problem for Unit 4 is to select the correct material of construction for tower packing in a distillation tower. The case specifically is: in a column distilling benzene and n-heptane, can we use a teflon packing? Is this the correct choice? This case problem requires that we look at the interaction amongst three surfaces and introduce the idea of a contact angle and how it varies as a function of state properties and solid systems, especially the solid roughness. The concept is defined for a solid-liquid-liquid or a three-liquid system and Young's equation is introduced. The characteristics of contact angles depend upon advancing versus receding hysteresis effect, the inhomogeneities of the solid and the roughness ratio. The sensitivity of contact angle to the force fields in the immediate vicinity of the contact line, and the importance of the outermost adsorbed surface are illustrated. The concepts of critical surface tension for a solid and autophobicity are introduced. Methods of estimating the contact angle from surface tension data and correcting for

mutual solubility of the various phases are given. Finally, the relationship between work of cohesion, work of adhesion and spreading coefficient are given. This interaction is illustrated through the various possible conditions for engulfing, particle engulfing or complete engulfing of a particulate when it is at a moving boundary. The dynamic behaviour of contact line and the flow of slugs of material through capillaries and the wetting of a fluid in coating processes are described. The summary of the key equations including the definition of the capillary number are as follows.

Young's Equation:

$$\gamma_{I-II} \cos \theta = \gamma_{I-III,2} - \gamma_{II-III,1}$$

for gas-liquid-solid

$$\gamma_{I-II} \cos \theta = \gamma_{I-III} - \gamma_{II-III} - \pi_{III,2} + \pi_{II-III,1}$$

for liquid-liquid-solid

$$\begin{aligned} \gamma_{I-II} \cos \theta_{123} &= \gamma_{I-III} - \gamma_{II-III} - \pi_{III,2} - \pi_{III,1} \\ &\quad - \pi_{I-III,2} + \pi_{II-III,1} \end{aligned}$$

Cassie equation for inhomogeneous solid

$$\cos \theta = n_1 \cos \theta_1 + n_2 \cos \theta_2$$

Wenzel's result for rough surfaces

$$\gamma_{I-II} \cos \theta' = r(\gamma_{I-III} - \gamma_{II-III})$$

We defined advancing and receding angles in terms of an intrinsic angle θ_E

For low energy solids, Zisman defined a critical surface tension for a solid, γ_c , which indicated that a fluid with $\gamma_{I-II} < \gamma_c$ would spread over the solid, whereas if $\gamma_{I-II} > \gamma_c$, it will not spread.

For most high energy solids (with $\gamma_{I-II} > 100 \text{ mN}\cdot\text{m}^{-1}$), most liquids spread over these solids except autophobic liquids that will not because the bulk liquid cannot spread over its own adsorbed species.

The work of cohesion is $W_c \cong 2 \gamma_{II-V}$

The work of adhesion is $W_A = \gamma_{III} + \gamma_{I-II} - \gamma_{II-III}$

The spreading coefficient is $W_A - W_c$

For example

$$S_1 \cong \gamma_{II-III} - (\gamma_{I-III} + \gamma_{I-II})$$

The spreading coefficient can be used to predict engulfment or rejection. For dynamic behaviour, the flow through a capillary is given as

$$(\Delta P) D = 4n \gamma_{I-II} (\cos \phi_R - \cos \phi_A)$$

A significant dimensionless group is the Capil-

lary number defined as

$$Ca = \frac{V_{CL} \mu_{II}}{\gamma_{I-II}}$$

Based on this information we could use the critical surface tension and the surface of the material being distilled (in this case benzene and normal heptane) to show that this choice of teflon would give film instability and non-wetting of the packing would result. As in other chapters we extend the concept of contact angle to the design of condensers, and specifically promoting drop-wise condensation to the design of reboilers, boiling phenomena and to film breakup in a tube two-bundle of a nuclear reactor to prevent dry patch formation. This is also related to polymerization reactors, to oil spill cleanup and to detergency, and finally to tertiary oil recovery.

Table 2 leads off the case problem for Unit 5. This illustrates that for different distillation conditions we get strange behaviour. To understand this behaviour we lead into a study of how the surface tension varies as a function of temperature, pressure, concentration, applied electrical field, curvature and time. After this exploration (which includes the Krafft temperature, water, surfactant and co-surfactant systems, and the effect of electrolyte on surface tension behaviour), we can use this information to lead into Marangoni type instability analysis. We start with macro and micro generated flows based on a temperature difference and then move on to the same type of flows as based on concentration variation. The application is not only to this case problem of looking at surface tension positive and surface tension negative systems and their use in understanding distillation behaviour, but in the drying of paint films, the conditions for a solvent extraction column, the stability of thin films in heat

TABLE 2
Unexpected Behaviour

Location/ Operation	Device	Chemicals	Observation
Edmonton, distillation	30 sieve tray column	n-heptane toluene	plate efficiency abnormally high, floods easily
Glace Bay, distillation	12 m Pall ring packed tower	benzene cyclohexane with azeotrope as the distillate product	required HTU almost double what we expected

exchanger and wiped film evaporator systems and in gas adsorption. We have been fortunate enough to obtain films from Royal Dutch Shell, Dr. Harvey Palmer at the University of Rochester, Dr. J. C. Berg, the University of Washington and Dr. Keith Brimacombe, the University of British Columbia, that visually illustrate this behaviour.

The next unit presents the case problem of trying to design an adhering system that will bind a plastic to a metal. This introduces the attractive force between two surfaces of condensed media. The emphasis in the overview is on the microscopic, or Hamaker, approach—although references are made to the Lifschitz and Ninhan and Persegian methods of estimating the attractive force between two surfaces. Various methods of estimating the Hamaker constant and accommodating for the attractive forces between various configurations are illustrated. Worked case examples include the attractive force between drops of chlorobenzene in water and the same drops coated with a monolayer of surfactant. When it comes to the adhesion question the additional aspects of the viscosity and flowability of the adherent and the surface area of contact between the two surfaces is also important. The application of these ideas to the production of pellets is illustrated with case examples.

Unit 7 explores the possibility of foam fractionation as a technique to remove some of the emulsifier that gets into the waste water from our process. This leads to the concept of surface concentration, methods of defining it, modelling it and measuring it. Our emphasis is on the indirect mass balance and the indirect thermodynamic balance (Gibbs adsorption isotherm technique). The methods of estimating based on heats of immersion and calorimetry are discussed briefly as are the various models for relating surface concentration to bulk concentration. The case problem, namely the design of the waste treatment plant, is worked out. The ideas are extended to adsorption and mass transfer in a solvent extraction column and where the surfaces are contaminated with surfactant and to the adsorption of emulsifier on latex.

A very large unit is on surface charge and the stability of dispersions. Many problems can be used to illustrate this application although our initial focus is on the decanter design and coalescence. The description of surface charge parallels the description of surface concentration (the only

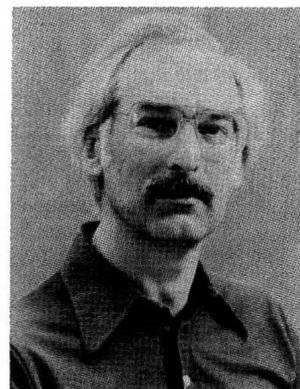
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Research on

CLEANING UP IN SAN DIEGO

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UNDERGRADUATE STUDENTS HAVE an opportunity for exposure to research through a number of methods utilized by many departments. Seniors often attend their department's graduate research seminar, which brings visitors to campus from other academic and industrial research laboratories. Independent study projects, and some senior courses, require exposure to the research literature. In most of these cases, one sees research at the end of the process—the reporting of completed work, usually after it has been tied up into a neat, coherent, package—as opposed to viewing the work during its stages of *evolution* and *aggravation*.

In this article I would like to describe how we came to begin studies in a specific field, and how

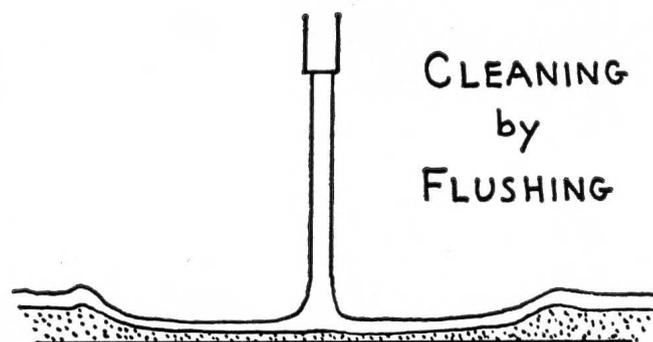
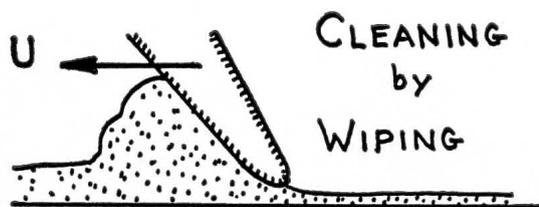


FIGURE 1. Liquid film may be removed from a surface by wiping, or flushing.

our successes and failures have led to the evolution of a set of research programs that now involve a number of graduate students in our chemical engineering program.

For some years we had carried on a research program aimed at elucidating some of the fluid dynamic phenomena associated with the coating of liquids onto moving surfaces [1, 2]. In such a field of study one examines the process by which a liquid film is purposefully and quantitatively spread onto a solid surface. But what of the inverse process: the *removal* of a film of liquid from a solid surface?

Consider, as an example, the situation in which a liquid is spilled upon a surface, and subsequently must be removed from that surface. How is that to be done? Two "generic" methods might come to mind: flushing with a jet of a second liquid, and wiping the surface with a second, clean, surface.

Fig. 1 shows in a schematic way the processes of interest. It is immediately apparent that a number of questions arise that could form the basis for several laboratory studies and that lead to a number of theoretical inquiries as well. For example

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- How does the wiper angle affect the residual film thickness?
- Does the liquid rheology play any role?
- Does the speed of wiping matter?
- Is a steady jet more effective than a pulsed jet?

While these questions are relevant, they ignore one important feature associated with the problem of removing liquids from surfaces: the role of surface roughness. Fig. 2 suggests, at a microscopic scale, the fact that liquid spilled upon a surface may be entrapped within the cavities



FIGURE 2. A real surface is rough, and can trap contaminant in its surface cavities.

that make up the architecture, or roughness, characteristic of real surfaces. Now one may raise additional questions

- Can an external flow field invade a small cavity in a surface and displace a contaminant from that cavity?
- If displacement does not occur, can circulation be induced within the cavity, and to what extent will that aid removal of the contaminant by diffusive processes?
- Is it possible to characterize surface roughness in a quantitative manner, in a way that provides a measure of how difficult a surface is to clean?

With a little more thought it should occur to one that if the interest is in the cleaning of rough surfaces, there may be interest in cleaning down to such a level that practically all of the original contaminating liquid film has been removed, and all that remains is the very small amount of liquid remaining in the cavities. Now two additional questions arise

- How does one measure residual liquid at such a low level?
- How does one reproducibly create an initial liquid film of very small thickness on a surface of interest?

At some point in the evolution of a research program one must stop asking questions and begin answering them. Of course, the reality is that in a good research program the attempt to provide answers to preliminary questions serve primarily to raise additional questions, and at the same time provides new directions to the research program. This, indeed, is what has happened in our own studies in this field. Let us turn, then, to a description of the current status of our research program.

The novelty that arises in our study lies in the fact that the jet impacts not on a rigid plate, but upon a thin layer of viscous liquid. How does this change the physics of the problem?

SPREADING A VERY THIN FILM OF LIQUID

Fig. 3 shows a sketch of the technique we now use for spreading a thin film of liquid on a surface of interest to us. A rigid disk is attached to the axis of a shaft in such a way that the disk can be rotated at high speed about its axis. A drop of the contaminating liquid is placed upon the surface, and the disk is set into rotation. Centrifugal forces cause the drop to spread into a thin film. This so-called rotating disk apparatus is not novel: the technique is used commercially for the creation of thin films in a number of areas of technology.

It would suffice to say that the technique works, and provides the initial films for our studies of removal. However, in an academic research environment, and sometimes in an industrial setting, the method itself may become the focus of interest. The flow of thin liquid films is not well understood, although thin film phenomena occur widely in many areas of chemical engineering. Indeed, one may create a sub-program of research from this spinning disk system, although the system evolved only as a means to a different end—the creation of a sample film for our cleaning studies. For example, one may raise the follow-

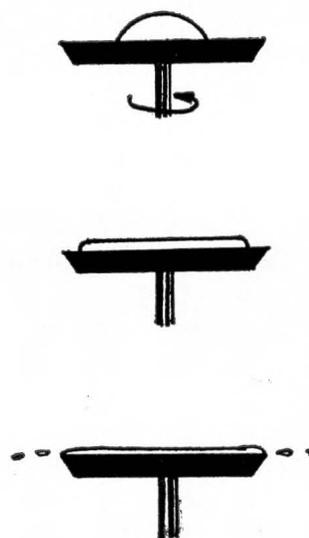


FIGURE 3. A thin liquid film may be spread on a surface by spinning.

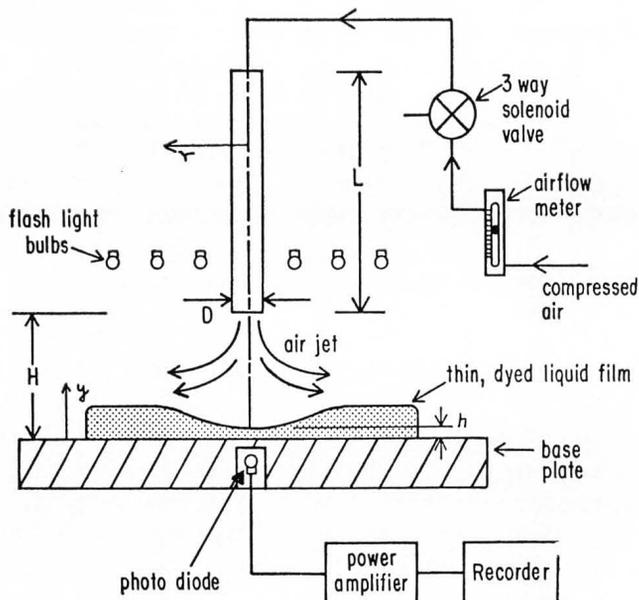


FIGURE 4. Schematic of apparatus for study of removal of a liquid film by an air jet.

ing questions

- How do the surface tension and fluid viscosity interact to control the rate of spreading of the liquid film?
- What is the role of surface roughness in spreading kinetics?

It should be emphasized here that questions such as those raised above have in fact been the focus of other research programs. There exists a large literature in the field of wetting kinetics, and in the study of moving interfaces [3, 4, 5]. Nevertheless, one finds in studying the literature that many unanswered, and interesting, questions remain to be pursued.

Instead of continuing with a detailed discussion of this area of our work, let us pass on to another aspect more directly related to the business of liquid film removal.

A SIMPLE MODEL OF LIQUID FILM REMOVAL

One must always attempt to understand the physics of the phenomena under study. A useful first step toward that goal is the creation of a very simple mathematical model that incorporates the major physical events that affect the process of interest. Although the model may not be in sufficient quantitative agreement with observation to serve as a useful description of the process, it is often the case that the simple model serves to fix certain ideas that determine future directions of the experimental program, and pro-

vides some guidance toward creation of a more accurate and satisfying theory.

Fig. 4 shows a schematic of a very simple apparatus for the study of some aspects of the kinetics of liquid film removal under the action of a fluid jet. A thin film is spread on a plate of transparent acrylic, and an air jet is blown on the surface. The action of the jet causes the liquid film to be displaced radially, leaving a clean area under the jet. The liquid is dyed, and an optical method, suggested in the figure, is easily used to measure the rate of thinning of the film in the region directly under the jet. Note that the simplicity of this experiment is such that the experiment deals with an isolated and very specific piece of the whole problem of surface cleaning. The goal at this stage was not to complete the research program, but to perform some simple experiments that would shed some light on the physics of the processes of interest to us, and that would at the same time explore some possible experimental techniques that might be useful in other aspects of the program. *Research is an evolutionary process.*

How does one produce a simple model of the process suggested in Fig. 4? The problem of a turbulent jet impacting upon a rigid surface normal to the jet axis is a classic problem in fluid dynamics. One may find solutions for the

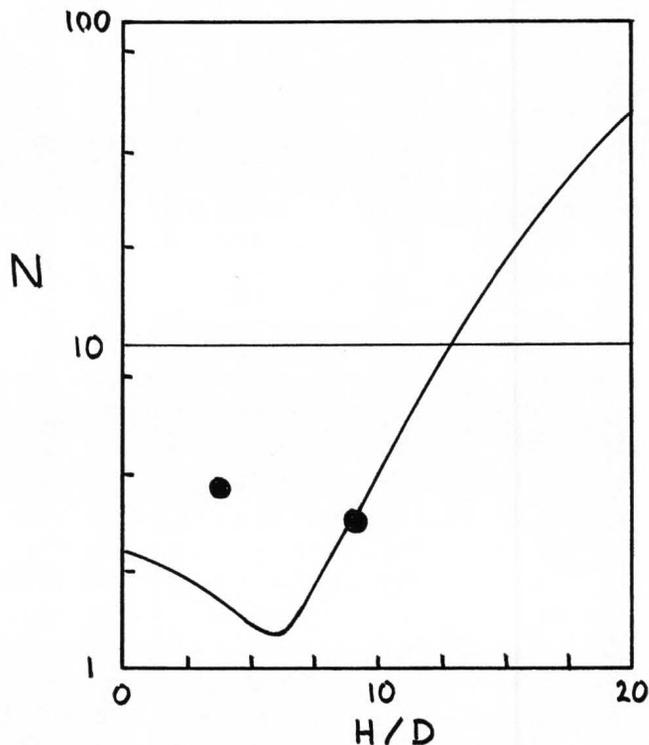


FIGURE 5. Data in support of a very simple model of film removal.

**One must always attempt to understand the physics of the phenomena under study.
A useful first step toward that goal is the creation of a very simple mathematical model that incorporates
the major physical events that affect the process of interest.**

velocity and pressure fields in the neighborhood of the stagnation point, as well as experimental data relevant to this flow field [6]. The novelty that arises in our study lies in the fact that the jet impacts not on a rigid plate, but upon a thin layer of viscous liquid. How does this change the physics of the problem? Perhaps very little!

For a first model of the process, we assumed that the jet flow was unaffected by the presence of the underlying liquid layer. In addition, we assumed that the ability of the jet to displace the liquid film was due primarily to the pressure exerted by the jet, which created a kind of squeezing flow in the underlying liquid film. These assumptions are certainly suspect, but they are worth pursuing because:

- They permit the use of existing theory for impinging jets.
- They permit the use of existing theory for squeezing flows.

In short, by beginning with a simple model one may quickly learn something about the physics of the phenomena of interest, with a minimal expenditure of time and energy.

Such a model has been developed by us and Fig. 5 shows the expectation that follows from the model. The half-time, the time for the film to be reduced to half its initial thickness, is predicted to depend upon parameters that appear in a dimensionless group N , defined as

$$N = \rho u_0^2 h_0^2 t_{1/2} / \mu D^2 \quad (1)$$

where

- ρ = jet density
- u_0 = mean jet velocity
- D = initial jet diameter
- h_0 = initial liquid film thickness
- μ = liquid film viscosity
- $t_{1/2}$ = half-time

According to this model, one expects N to depend only upon the "stand-off distance" of the jet. (See Fig. 4.)

The two data points in Fig. 5 really represent the average N -value of many experiments, in which liquid viscosity, initial film thickness, and jet speed, were varied. Considering the simplicity of the model, the agreement is quite good. Still, a key question is left unanswered by this particular demonstration

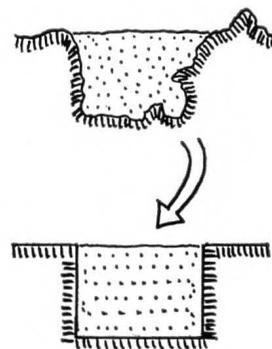


FIGURE 6. Idealization of a roughness element by a rectangular cavity.

- Since an air jet is essentially inviscid, would a liquid jet behave in the same manner?

Studies along lines implied by this question are in progress, but will not be described here. Instead let us turn to another aspect of the research program.

A MODEL OF REMOVAL FROM A CAVITY

Fig. 6 shows the transformation of a roughness element in a surface into an idealized two-dimensional rectangular cavity. If one can learn something about the ability of an external flow to aid the removal of a contaminant from such an idealized cavity, it should be possible to extend this knowledge to the more realistic but complex case that corresponds to a real rough surface. Thus we raise the following questions

- Is it possible to simplify the geometry and the flow field to the point that it is possible to carry out a theoretical model of the removal process?
- Is it possible to perform laboratory experiments on a cavity that is large enough to be instrumented, and then translate the results so that they apply to a micron-sized cavity?

Theoretical models have been developed, using numerical methods, which allow solution of the equations that describe flow external to the cavity, and the development of an internal circulation within the cavity induced by that external flow. The model allows for diffusion of contaminant from the cavity. In addition it is possible to add chemical reaction to the model, and in this way

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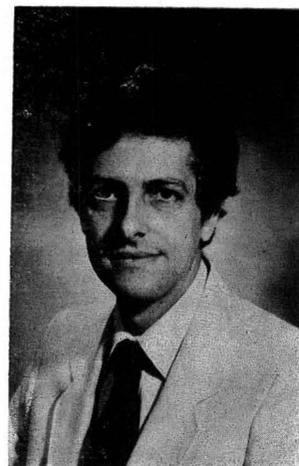
IT IS WIDELY recognized that there is a need for better understanding of the chemical and physical phenomena involved in the combustion and gasification of fuels such as coal and oil. Such understanding could lead to the development of more efficient methods of preparation and conversion. That would reduce the levels of pollution and operating costs.

Various aspects related to combustion are presently being investigated at Michigan Technological University, MTU. Work on characterizing and modifying diesel emission is being performed in the Mechanical Engineering Department [1, 2]. Semiquantitative dose-response data on the biological activity of exhaust particulate emission [3] is being obtained at the Biology Department using the Ames Test [4] as modified by Belser et al [5]. Bacterial mutagenicity tests are widely used today because of the correlation between mutagenicity in bacteria and carcinogenicity in humans [6]. In the Chemistry and Chemical Engineering Department research focuses to a large extent on coal pyrolysis, combustion and corrosion. Experiments on the effect of flame retardants on the smoking tendency of high and low temperature polymers is underway. In the following paragraphs only the work related to coal will be discussed.

COAL RELATED RESEARCH

Since the renewed interest in coal, numerous studies were performed as may be judged from the proliferation of publications and the rise in the number of symposia and technical meetings on the subject [7]. Since the work is being performed in various laboratories it is not surprising that there is much overlapping of effort. For this reason papers that describe the state of the art [8, 9] are needed to make us aware of other people's activities and to identify areas in need of further investigation.

The main thrust of the work which is the



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subject of this paper was aimed at improving coal combustion and reducing operating expenses by using additives (catalysts). The introduction of additives was intended to tackle certain problems in industrial boilers such as 1) to improve combustion by reducing the unburned carbon in the ash and carbon monoxide in fuel gas atmosphere, 2) reduce excess air and lower exit temperature to minimize the heat loss up the stack, 3) reduce particulate emissions into the atmosphere, and 4) control corrosion of tubes and other parts of a boiler. Single or mixed additives that produce some or all of the above effects exist [10-13]. They vary in composition, effectiveness and cost. Most of the additives studied fall into one of three groups: alkali metal salts (Li, Na, K), alkaline earth metal salts (Ca, Mg), and transition metal salts (Fe and Ni). The first group was extensively studied because of its influence on coal gasification and also for the purpose of understanding the corrosion mechanism. It is generally believed that alkali iron trisulphate complexes $[M_3Fe(SO_4)_3]$ where $M = Na, K$ are the principal contributors to high temperature coal-ash corrosion [14]. The alkali and sulfur constitute part of the impurities in the fuel. The production of the alkali metal complex requires the presence of sulphur trioxide. The rate of formation of SO_3 is related to the amount of SO_2 available.

Our studies on coal combustion parameters [12, 13] were performed in a tubular combustor (Fig. 1) and using thermal analytical techniques. The combustor construction was similar to that used by Horton et al. [15]; however the burner section was slightly modified for stability. Pulverized coal was fed to the top of the burner section using a screwfeeder into a downflow flat premixed flame of methane and air. The system shown in Fig. 1 had a number of windows which made it possible to probe the test furnace along its length for chemical species and solid material as well as to place metal specimens for studies on corrosion. Electron microscopy, X-ray analysis and Auger spectrometry were used to characterize the deposits on the metal specimens. This made it possible to probe the metal specimens to various depths.

In addition to the above combustor, a DuPont 950 thermogravimetric analyser (TGA) was used to obtain kinetic data related to coal decomposition. These instruments possess a high degree of precision and speed in producing data. It is also possible to observe continuously the change of mass (TG) and rate of mass change (DTG) with time or temperature. This makes it possible to observe details that are liable to be missed using a flow combustor. For example, mixed additives

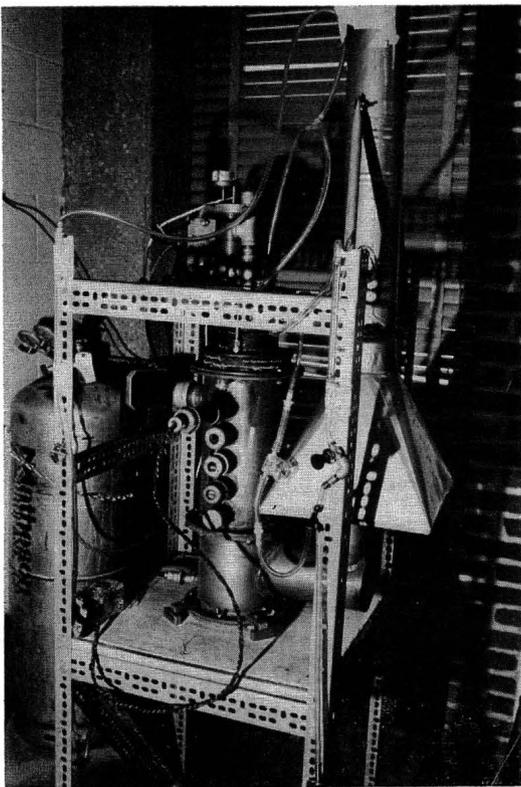


FIGURE 1. Coal combustor.

The main thrust of the work which is the subject of this paper was aimed at improving coal combustion and reducing operating expenses by using additives (catalysts).

are found to be more effective than single additives on an atom per atom basis. It is difficult to determine, for instance, in a steady-state flow system such as that used in our experiment, the time during the decomposition stage at which the synergetic effect of the mixed additive occurs. However this is a simple task in TGA work, since the decomposition profile is completely available. There is evidence that the promoting effect occurs mainly during the initial stage of coal conversion. In this region single additives inhibit decomposition of coal [13]. The TGA was found to be useful in identifying the experiments to be studied in the flow combustor and in performing corrosion-related studies under very controlled conditions.

Thermogravimetric analysis has been extensively used judging from the number of books and specialized journals. Nevertheless, several aspects need to be investigated to understand what is being measured

- The meaning of activation energies of solids such as coal obtained from TGA experiments is not clear.
- The values of the activation parameters are dependent on the operating conditions [16] such as heating rate and gas flow rate.
- To calculate E first order kinetics for coal decomposition is usually assumed using one thermogram obtained at one heating rate. However, it was proposed (on the basis of theoretical considerations) that methods involving more than one heating rate will give more precise values of E [17].

A detailed investigation of several methods, using the same coal, showed that methods using one heating rate are preferred. Methods which use multiple heating rates will give values of E which are dependent on the heating rate combination [18]. The latter method is also time consuming. In an attempt to explain the meaning of the activation energy obtained from TGA work the enthalpy of reaction, ΔH_R was measured using a Differential Thermal Analyser; DTA [13]. A linear relationship was found between E and $|\Delta H_R|$. This suggested the influence of the heat of reaction on the chemical change typical of elementary reactions [19] and would, therefore, reinforce the previous postulate that coal decomposition follows first order kinetics [20]. The change in

operating parameters such as heating rate will favor different reactions, thus producing different values of ΔH_R and E . Therefore, comparison of the effectiveness of different additives should be performed under identical operating conditions.

CONCLUSION

Much work is needed before one is able to completely understand the role played by additives in the combustion of coal used in industrial and utility boilers. The chemical state of the additive in promoting combustion of $\text{CO} \rightarrow \text{CO}_2$ is still speculative [8]. Also, the behavior of the coal during combustion will vary according to the physical state of the coal, i.e. molten or dry. It will also depend on the aerodynamic properties such as density and shape and the adhesive quality known as the wettability of coal [21]. We also have to distinguish between combustion of small, and combustion (and gasification) of large, coal particles. □

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ChE book reviews

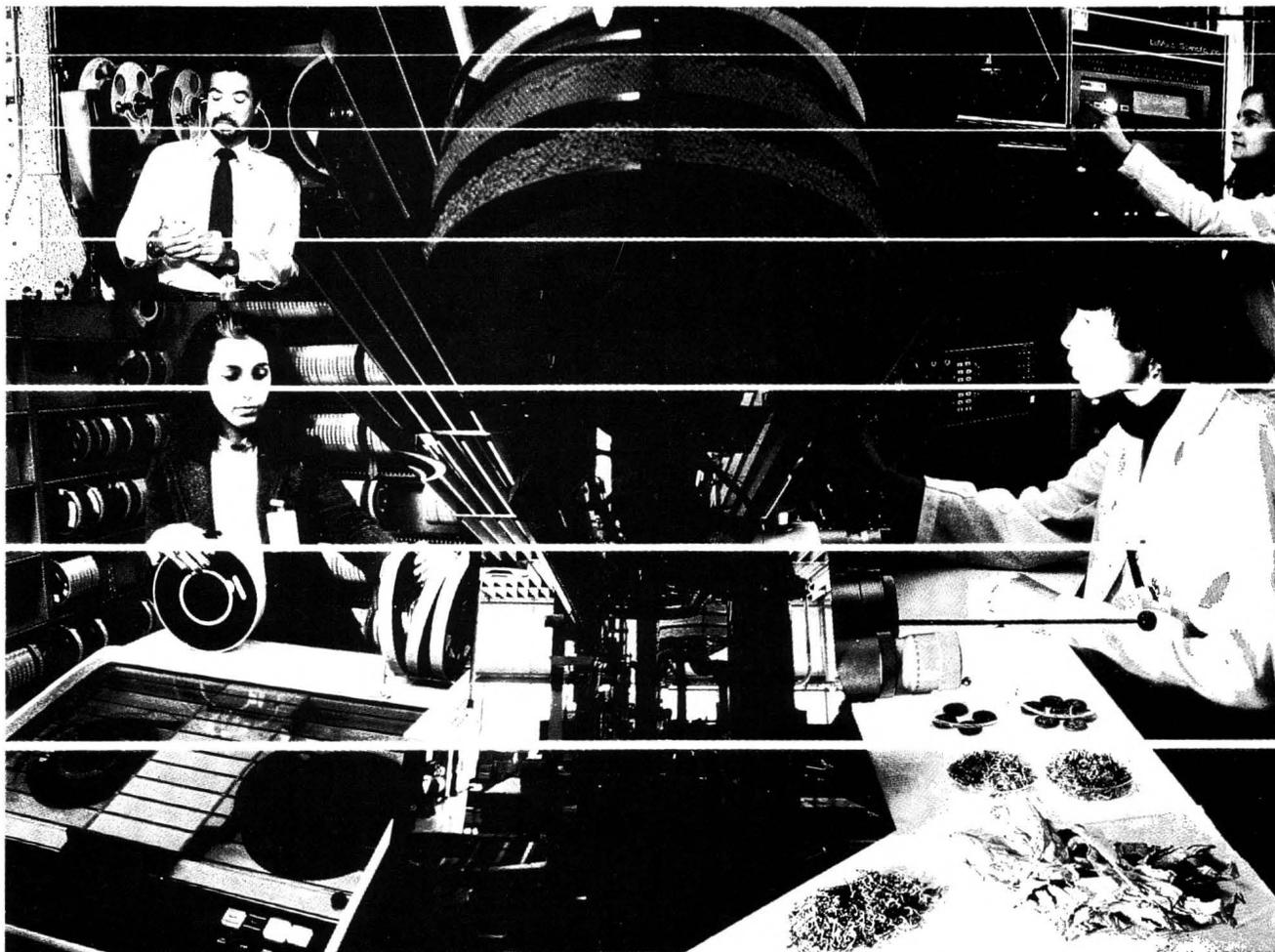
CHEMICAL REACTOR ANALYSIS AND DESIGN

By G. F. Froment and K. B. Bischoff
John Wiley and Sons, New York

Reviewed by
Arvind Varma
University of Notre Dame

This book is a welcome addition to the growing number of books now available in the area of reaction engineering. It is comprehensive, and contains more topics than are covered in most books. The book has two particularly strong points. One is the wealth of *real* examples, and the second is a

Continued on page 196.



PHOTOS—Michael Melford and Charles Harbutt

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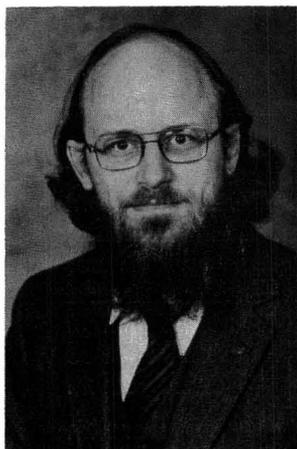
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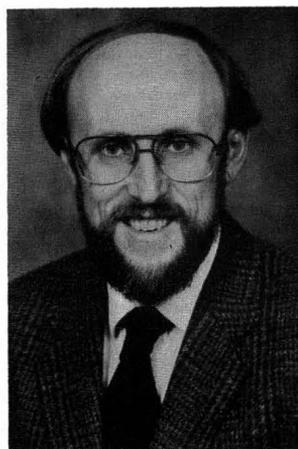
THE GRADUATE STUDENT'S GUIDE TO ACADEMIC JOB HUNTING

PHILLIP C. WANKAT AND
FRANK S. OREOVICZ
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West Lafayette, IN 47907*

IN EDUCATION AS IN industry, one of management's jobs is to train successors—qualified persons to carry on the excellence of the program or operation. To date, many faculties have not placed a very high premium on this responsibility. We suggest that the job can be simplified and that qualified students can be encouraged and helped to start an academic career. This paper will be addressed to graduate students to help them ease the transition to an academic career. We will look mainly at what a candidate does in preparing for an academic career and the steps he or she needs to take along the road to a job. We will also look at what the school does since this information is helpful to the candidate. Table 1



Phil Wankat received his BSChE from Purdue and his PhD from Princeton. He is a professor of chemical engineering at Purdue. He has received several teaching awards at Purdue and earned an MS.Ed in Counseling (Purdue, 1982). Phil does research on separation methods with emphasis on cyclic separations, two-dimensional separations, large scale chromatography, and high gradient magnetic separation. (L)



Frank Oreovicz has a PhD in English (Penn State) and a BS in Physics (Illinois Institute of Technology). He has taught English and been the Assistant Director of the Center for Instructional Development in Engineering at Purdue. Currently, he is a communications specialist in the School of Chemical Engineering at Purdue. His professional interests include finding ways of using word processing to teach technical communication. (R)

provides a guide for the steps and we will refer to it throughout the paper.

WHAT THE CANDIDATE DOES

Most important is that you obtain an excellent education. You must learn how to do sound research. Obviously, each student does some sort of research, but you must have something to offer your potential school, something that is beyond the ordinary project. In addition to conducting research, be sure your experience includes research planning, proposal and report writing. Think in terms of what a prospective employer might require.

1. Develop a Resume. A resume can be used effectively to help you construct your scenario for the future. What it contains will tell you where your strengths are, and what is more important, it will show you what you haven't done. Since you've planned ahead and started early, there's still time for you to gain valuable experience and knowledge, especially in the following areas

- Teaching (try to get lecturing experience)
- Money raising (help with proposals)
- Presentations at meetings
- Paper writing
- References (get to know at least 3 professors well)

By working closely with your advisor and other faculty, you can arrange to gain experience in all these areas.

2. Pre-screen. First, what openings are available? The usual locations for advertisements are Chemical Engineering Progress, Chemical and Engineering News, and ASEE Engineering Education News. However, since not all openings are listed, be sure to ask your faculty contacts for suggestions and watch the department's bulletin boards. What openings are you going to apply for? Do your interests and philosophies match the school's? Obviously, to make this decision you must first know your goals, both personal and professional. For example, is geographical location important to you? Is size of school a factor? Religious affiliation? And so on. Where do you find

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information about schools? Several resource guides are available:

- ACS Directory of Graduate Research
- ASEE, March issue of *Engineering Education*
- AIChE Fall Student Member's Bulletin
- Chemical Engineering Faculties, AIChE
- Ratings in *Chronicle of Higher Education*
- Graduate student brochures from schools
- Professors—ask.

What are some things you might look for? Teaching loads, school resources, research areas, promotion policies, and reputation should all be considered. Careful screening at this stage can save time and frustration, even embarrassment, later. There is no point in applying to a school if you wouldn't want to teach there. Use a large

TABLE 1
Chronological Steps in the Academic Job Hunt

CANDIDATE	SCHOOL
Does sound research and develops professional goals	Develops an ongoing tradition of excellence which makes school an attractive place to teach and to do research
Decides on academic career	Needs new professor; sets criteria
Develops resume; picks references	
Prescreens school openings	Advertises
Writes individual cover letter & mails with resume	Does initial screening
	Ask for reference letters
Makes sure references are sent	
	Decide to invite for visit
Decide to accept; set up time for visit	
Prepare for seminar; get info about the school	Set up schedule of visit
Visit: Social and individual talks, seminar	
Follow-up: thank you letter and expenses	Decision: offer a job?
Negotiation	Negotiation
Acceptance	
	Prepare place for new professor
Prepare for first year	
Move to new position	

This paper will be addressed to graduate students to help them ease the transition to an academic career . . . mainly at what a candidate does in preparing for (that) career . . .

sheet of paper and make up a rating chart to compare the schools.

3. Send letter plus resume. Your aim in sending a letter with a resume is to convince the school that you are worthy of consideration. You won't accomplish this aim, however, if you do a blanket mailing and send out a standard letter to many schools. Tailor the cover letter for the particular needs of the hiring department, remembering of course to be forthright in listing your qualifications. Make sure that all critical information is also in the resume. A cover letter may not be circulated as widely, or at all, within the department. Since the typical resume is short, you may need to include important additional documents with it. These may include key submitted papers or papers published in proceedings. If you don't have any publications, now may be a good time to start thinking about writing some.

What is a good time to start applying? The bottom line is that sending nothing is better than sending half-formed ideas. You must have solid research to report, but you don't want to wait until the last minute. Wait until you have at least one paper written and submitted.

Another step in pre-planning involves references. Once you get a response to your letter, make sure that reference letters are sent. These are often a key factor in a school's decision to invite you for an interview; consequently, you must choose the writers carefully. Obviously, your dissertation advisor **must** write a key letter, but others may have a great deal of influence in the "old boy" network. Establish contacts early in your career as a graduate student and get to know faculty members who are competent to judge your work.

4. Plan trip. Now that you've received a favorable response and have been invited to visit the campus, several preparatory steps can make that visit easier and more productive. Most critical is the preparation for the seminar you'll be expected to give. Your success depends on how well you prepare because a good presentation will show the school that you can do research, organize ideas, communicate, teach, and handle questions while under pressure.

The first step to writing an effective presentation is audience analysis. Your listeners will be intelligent individuals but few will be experts in your field. Consequently, don't insult the intelligence of some by talking down to them, that is, by explaining matters that should be obvious to a general engineering audience; and don't lose others in an attempt to impress them with arcane minutiae. Give the presentation before your research group and invite any faculty members who may be able to offer advice. Ask for difficult questions and get accustomed to being put on the spot.

Attend seminars and note the qualities that make good presentations effective (and learn from

Schools want candidates who will "land running" when they begin their jobs, who know where they want to go. A vague idea of wanting "to teach and do research" is not enough.

the failures). Positive aspects will include manner of presentation—style of delivery, vocal qualities—and effective use of media, usually slide or overhead projector.

For the visit to be successful you must also be prepared to have a clear idea of the directions you expect your career to take. Schools want candidates who will "land running" when they begin their jobs, who know where they want to go. A vague idea of wanting "to teach and do research" is not enough. A corollary is to do research on the school and faculty to discover what their goals are. A quick reading of the department's graduate brochure will acquaint you with the interests of the faculty and give you an idea of where you might fit in. Not only will this information be useful to you, but it will enable you to show them that you know who they are, that you know which faculty you want to talk to and which facilities you want to see. You can only enhance your image as an organized and motivated individual when you show the foresight to ask about computer facilities, special research equipment available and so on.

VISIT

The visit to the campus offers you a great opportunity to shine personally and professionally. The social aspects involve all the typical matters of etiquette—listen to others, learn names, don't drink too much, and so on. But in an attempt to be

all things to everyone don't spread yourself too thin. If the next day looks to be hectic, don't be afraid to be assertive about the need for sleep the night before.

The visit works both ways for the two parties. The school wants to learn everything about you, but you should also take the initiative and ask questions about matters important to your future. For example, what are the facilities like, not just the immediate ones but the support facilities—university computer system, etc.; what are the promotion policies; talk with young faculty about their morale; will graduate students be available; availability of summer support; and teaching load. These questions will affect you from the minute you sign the contract, so you better get answers fast. The department head can answer many of these questions, but many times answers appear in the unlikeliest of places. Keep attuned to conversations with those not at the center of the power structure, especially students and untenured faculty.

The key words for the seminar are "be prepared." Since schools use the seminar to judge your ability to teach, to do research, and to think on your feet, the occasion is very important. Being prepared will help to make the "hot seat" more comfortable when the time comes. Sometimes, however, no amount of preparation will cover everything; inevitably, someone asks a question which leaves you groping. Whatever you do, don't become defensive or hostile. First, make sure you understand the question; rephrase it or ask for it to be repeated. If nothing else this pause will give you time to think. In the interim you might think of an answer. But, be willing to say "I don't know" or "we haven't determined that yet."

FOLLOW-UP

A simple thank-you letter is all that is needed. Include a statement of your expenses and of course be honest in your figures. If several visits were combined into one trip, be sure to pro-rate the expenses. Don't pad and don't try to make money on the trip. If you promised to send follow-up information, papers, or articles, do so immediately. The personal habits you display now will reinforce the good impression you made during the visit.

NEGOTIATION

You've been offered the job: At this point you have the most negotiating power. Spell out what you need and try to get it—within "reason" of

The first step to writing an effective presentation is audience analysis. Your listeners will be intelligent individuals but few will be experts in your field. Consequently, don't insult the intelligence of some by talking down to them . . . by explaining matters that should be obvious to a general engineering audience.

course. And do so in writing. This is required not because a lack of trust exists, but because misunderstandings arise between even the best intentioned of parties. Some of the negotiable items are the following: computing facilities, equipment, grad student support, lab space, salary, starting date, start-up money for equipment, summer support, teaching assignments, and travel money.

ACCEPTANCE

If the offer is for the job of a lifetime or if it's the only one that's likely to come along, then by all means ACCEPT immediately. If you have several, weigh carefully. Remember that you're making a serious commitment. First accepting an offer and then withdrawing it to accept another offer is not ethical behavior. Note too that the salary or fringe benefits from School A will not mean so much in a few years if the location is such that your hay fever won't be able to adjust to the climate; School B, on the other hand, is ideally suited in this regard, although its starting offer isn't as liberal. And so on. If you still have a visit or two to make then give the schools a date by which you will make a decision. But don't keep the school waiting too long. They need to know.

PREPARE FOR FIRST YEAR

Be sure to finish your PhD. Don't expect to be able to finish writing while on the job. Once you begin teaching, you will be under pressure to produce immediately. Also finish most of the writing of papers arising from your graduate research. When promotion time comes, you will be judged on your new ideas, not the spin-offs of the past.

MOVE TO NEW POSITION

The first year will be an acclimating and settling in experience. First proposals will have to be sent out, research programs initiated, graduate students chosen, first courses developed: in short, the ropes will have to be learned. This is a time to develop your identity. The work you will be judged on will come from you and your graduate students. Since the most important articles will be those in high quality refereed journals, select carefully where you send manuscripts.

You will also be judged on your teaching—not as much as on your research, but bad teaching will hurt you. Excellent teaching helps if you already have good research. Teaching skills can be improved, even learned. Since good teaching may take no more time than poor teaching, find out if your school has an instructional services center. Such centers often offer short courses in improving teaching skills or your department may have a course or structured teaching experience.

WHAT THE SCHOOL DOES

What is the school looking for in a candidate? A research institution wants future research winners, good, but not necessarily outstanding, teachers, and dependable individuals. In choosing their ideal they go through the steps in Table 1. Their choice may also depend on whether they want to fill a gap in teaching or research, or build up a strong area of excellence. To succeed in their selection they will use the screening process, the reference letters, and visit. They will look for potential and sound accomplishment. But they may also go beyond the immediate papers available. They may compare notes with other schools. Schools also know what the going rates for salaries, equipment, and teaching loads are at competing institutions. A carry-over negative attitude to a visit may be communicated to your immediate prospect. So treat everyone respectfully and honestly, even if you decide during the visit that you would not accept an offer.

CONCLUSION

We have tried to formalize the process for searching for an academic job. Our experience has shown that too often students go through a haphazard procedure, getting advice here and there. Attention to details such as noted here should help make life simpler for many graduate students. □

ACKNOWLEDGMENT

Many of the ideas in this article were gleaned from a panel discussion held at Purdue University. The panel members were Drs. Ron Andres, Nick Delgass, Lowell Koppel, Richard Mallinson, Frank Oreovicz, and Phil Wankat.

GRADUATE EDUCATION WINS IN INTERSTATE RIVALRY

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Pullman, WA 99164

GEORGE M. SIMMONS
University of Idaho
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OUR DEPARTMENTS OF chemical engineering at Washington State University (WSU) and the University of Idaho (UI) have been successfully coordinating their graduate offerings for the past two years. The universities are just eight miles apart and travel time from classroom to classroom is under thirty minutes. Like many similarly sized graduate programs in the country, we lacked the critical mass to sustain an expanded course offering so desirable for a quality doctorate program. By joining forces for graduate course-work, we have a combined pool of about forty full time graduate students and fourteen full time graduate faculty, which allows for a wide variety of course offerings.

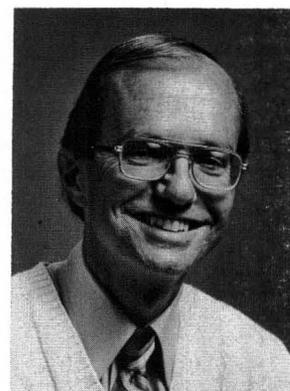
Historically, most of our entering graduate students pursue the Master of Science degree, with far fewer numbers opting and being accepted for doctorate work. To meet the needs of the master's student, a basic core of graduate level courses must be offered every year. This requirement left little room in the teaching schedule to offer additional courses for the doctorate program and we relied extensively on the departments of math, chemistry, and other engineering disciplines. Adding to this problem was the desire and need on the part of the faculty to teach advanced courses in their particular area of expertise.

Prior to our decision to formalize our cooperation, we had encouraged students to take classes of interest at the other university. This non-intervention approach had three major obstacles: the different academic calendars, arranging compatible course schedules, and lack of course offerings.

Calendar. The two universities both operate on the semester system, however UI has an early



William J. Thomson received his Ph.D. in Chemical Engineering from the University of Idaho in 1969. His research interests are in kinetics and catalysis and he has been teaching chemical engineering for 14 years. He is currently chair of the Chemical Engineering Department at Washington State University. (L)



George M. Simmons received his Ph.D. in 1970 from Stanford; he worked in the solid propulsion group at the Jet Propulsion Laboratory before joining the University of Idaho faculty in 1975. Dr. Simmons, whose main research areas are in thermochemical biomass decomposition and in geothermal energy utilization is currently professor and chairman of the Chemical Engineering Department at the University of Idaho. (R)

start (late August) compared to WSU (mid to late September). While UI was starting its second semester, WSU had three weeks remaining on their first. Scheduling of courses was then difficult in that we had to interface four separate schedules. An additional (and remaining) problem is that neither professors nor students are able to take advantage of a traditional spring break, which occurs at different times at the two universities.

Course Scheduling. A course scheduled in the middle of the day in effect wasted nearly a half day in attending one class at the other campus. Even though the transit time is about 25 minutes, a student finishing a class at one campus at 10 am could not start a class at the other campus until 11 am. Coupled with the built-in inertia of getting started on a new task (coursework or research), we found that students taking classes at the other university were wasting a lot of valuable time. There were also many conflicts in the two schedules.

Course Availability. Since we are obligated to provide a basic graduate offering for the Master of Science program, we found that we were in fact teaching nearly the same courses; there was seldom any advantage in taking courses across the state line.

Once we agreed to coordinate our graduate offerings we were forced to address these and other unforeseen problems. We did, however, have enthusiastic support from the administrative officers at both universities. We have resolved most of these problems in a quite satisfactory way and wanted to share our experiences.

TABLE I
Joint Graduate Course Offerings

FALL 1981

Transport Phenomena (WSU)
Polymer Reactor Engineering (WSU)
Chemical Engineering Analysis I (UI)
 process simulation
Advanced Plant Design (UI)

SPRING 1982

Chemical Engineering Kinetics (UI)*
Biochemical Engineering (UI)*
ChE Thermodynamics (WSU)
Digital Process Control (WSU)*

FALL 1982

Transport Phenomena (UI)*
Advanced Plant Design (UI)
Chemical Engineering Analysis I (WSU)*
ChE Thermodynamics (WSU)*

SPRING 1983

Multi Phase Transport & Reactions (WSU)
Chemical Engineering Kinetics (WSU)
Chemical Engineering Analysis II (UI)
 statistics and experimental design
Mass Transfer Operations I (UI)
 diffusional

Fall 1983†

Transport Phenomena (WSU)
ChE Thermodynamics (WSU)
Chemical Engineering Analysis I (UI & WSU)
Advanced Heat Transfer (UI)

SPRING 1984†

Chemical Engineering Kinetics (UI)
Biochemical Engineering (UI)
Advanced Extractive Metallurgy (WSU)
Mass Transfer Operations II (WSU)
 physicochemical hydrodynamics

*Taught via two-way microwave

†Scheduled for 1983/84

FALL 1983

By joining forces for graduate course-work, we have a combined pool of about forty full time graduate students and fourteen full time graduate faculty, which allows for a wide variety of course offerings.

DEVELOPMENT OF THE PROGRAM

First Attempts

The initiation of the cooperative course program took place in the spring of 1981 with a single course (ChE 523—Basic Concepts in Catalysis) which was taught at WSU. The difficulties encountered at that time were primarily involved with the paperwork of getting students registered, assigning grades and the everpresent problems associated with academic calendars at the two universities. The latter initially was solved by teaching the course on a compressed schedule so that it began on WSU's schedule (February) and ended on Idaho's schedule (mid-May). UI had previously adjusted its daily class schedule to start all classes on the half-hour; this change gave UI an extra class period and also fit well with the WSU schedule, which starts on the hour. We found the easiest way to deal with the paperwork was to simply cross-list in both university catalogs all the graduate courses in both departments. The formalities were soon in place and the bookkeeping problems were eliminated as obstacles.

The Basic Program

By the following semester (Fall, 1981), the basic elements of the program as we know it today were established. Certain "core" courses (Transport Phenomena, Chemical Engineering Analysis, Thermodynamics, and Chemical Engineering Kinetics) were identified as being common to both curricula; with the exception of Thermodynamics it was agreed to teach the core program in alternate years at each university. This sharing of core courses left room for several additional courses to be offered by our two faculties. Table I shows the courses which have been taught under this program since the fall of 1981 and those planned for the 1983/84 academic year.

The specific courses to be offered in a given year are decided in consultation between the two departments and are based on core requirements, faculty research interests and balanced teaching loads. While the core courses are taught each

Continued on page 194.

BOOK WRITING AND CHEMICAL ENGINEERING EDUCATION*

Rites, Rewards, and Responsibilities

"... of making many books there is no end; and much study is a weariness of the flesh."

Eccl. 12:12

R. BYRON BIRD

*University of Wisconsin-Madison
Madison, WI 53706*

ON THE WALL ABOVE my desk at home I have a map of Canada prepared by the cartographer Guillaume de L'isle in 1720. It shows the Great Lakes in about the correct relative positions, but their shapes are somewhat distorted. Much of the region, known at that time as La Nouvelle France, had been only partially explored, and consequently the map is clearly imperfect in the eyes of a 20th century American. The region to the west of Lake Superior was *terra incognita* in 1720. But incomplete as this map was it doubtless served explorers, government officials, and scholars of that time; subsequent explorations, many of them by canoe, led to better and better maps as the unknown gave way to the known. Every summer when I go canoeing in the Canadian "bush", I can imagine the frustrations of the early explorers as they tried to push ahead through the waterways with their imperfect maps. Even armed with the best maps of our time, made from aerial photographs, we occasionally have encountered errors that have cost us time and trouble (including the interchange of a 2-foot rapids and a 50-foot waterfall on the Balmoral River in Ontario).

The 1720 map over my desk serves as a constant reminder that current books on science and engineering represent only an imperfect summary of our present knowledge and that beyond the covers of these books is a vast *terra incognita* which will be explored and charted by

*This manuscript was prepared and presented for the Phillips Petroleum Company—Chemical Engineering Lectureship Award at Oklahoma State University on December 6, 1982. This lectureship series has been active since 1967 and is meant to recognize outstanding contributions to chemical engineering education.



Bob Bird was an undergraduate at the University of Maryland, received a B.S. in chemical engineering at the University of Illinois, did his doctoral studies in physical chemistry at the University of Wisconsin, and had a postdoctoral appointment in theoretical physics at the University of Amsterdam. He joined the staff of the Department of Chemical Engineering at the University of Wisconsin in 1953 and has been there ever since (except for teaching for one semester in Delft, in Kyoto, and in Nagoya) serving as its chairman during the period 1964-1968.

those who follow us. The books of the future will reflect the new discoveries and will present the subject material in sharper focus and in better perspective. Meanwhile we make do with the currently available books, recognizing that mistakes and misconceptions contained in them will occasionally result in confusion and disaster—just as the errors in the Canadian maps have plagued the canoeist.

In educational circles today we hear a great deal about *teaching* and *research* (or, more often, teaching vs. research—as though these were mutually exclusive activities!). However we hear very little about the activity of *book-writing*, which ought to be included as a third principal

One bit of advice that cannot be overemphasized: allot some time for physical exercise and relaxation during the period you are working on a manuscript. During periods of intense mental activity, the mind sometimes gets 'clogged up.' I have found that a good long hike (preferably alone) once a week is essential to good bookwriting.

activity of a university teacher since it is concerned directly with the production, evaluation, organization, and dissemination of new knowledge. Therefore I thought it might be useful to use this lecture to focus attention on the "rites, rewards, and responsibilities" of book authorship. Since I have had the pleasure and good fortune to co-author several books [1] perhaps I can offer some appropriate words of encouragement to aspiring writers and even a few helpful suggestions regarding the art of writing. Maybe I can help others avoid some of the mistakes I've made. From time to time I will cite specific personal experiences in order to avoid discussing the problems of authorship in the abstract.

It is not my intention to discuss the history of chemical engineering and the role that various books have played in the development of the discipline. A brief historical summary was prepared in 1957 by Dr. Thomas H. Chilton [2], and Professor Olaf A. Hougen's Bicentennial Lecture [3] on Chemical Engineering History in 1976 contains additional material on chemical engineering textbooks. Still more information is to be found in two recent collections of articles on the history of chemical engineering [4].

WHAT KINDS OF BOOKS DO CHEMICAL ENGINEERS NEED

A library of professional volumes includes various classes of books: (i) *edited volumes* to present very recent developments by teams of experts; (ii) *research monographs* to catalog and evaluate the research published in the preceding 5-10 years; (iii) *treatises* to give authoritative, encyclopedic coverage of one particular topic; (iv) *textbooks* to set forth the basic ideas in the field in a form suitable for students; (v) *handbooks* to summarize standard results of widespread use; and (vi) *design manuals* to provide up-to-date procedures for practicing engineers. Each of these categories has a different audience, and each requires special organizational talents. Generally speaking there is a flow of information from (i) towards (vi) in the above listing—that is, from innovative, exploratory, and (sometimes) impractical ideas of the researcher all the way to the time-tested and reliable tools of the practitioner.

Along the way many ideas and methods are inevitably discarded, and only the most useful material survives to the arena of industrial practice. But without this constant exploration of new ideas and subsequent filtration, a profession can stagnate and atrophy.

In a very real sense good books bring about change. Some material from research-level monographs gradually finds its way into graduate and then undergraduate textbooks. New textbooks create changes in college courses and curricula; they can also produce changes in teaching methods. Handbooks and design manuals can ultimately bring about improvements in production methods.

The very boundaries of what we mean by chemical engineering are determined to a significant extent by the textbooks. The publication of "Principles of Chemical Engineering," by Walker, Lewis, and McAdams [5] at MIT about 60 years ago shaped the field of chemical engineering for many decades afterwards. And the trilogy of books by Hougen, Watson, and Ragatz [6] showed how the ideas of thermodynamics, kinetics, and diffusion could be used in the solution of key chemical engineering problems. These books were particularly influential because of their incisive organization of large quantities of material and the timeliness of the examples and problems. The future definition of chemical engineering will be established by books of the same quality and insight, but in new areas.

What are some of these new areas that are crying out for authors? No one person can supply such a list, of course, but I'll offer a few ideas:

- **Thermodynamics from the point of view of differential geometry (based on some of the developments of Weinhold [7])**
- **Separations processes in solids purification, with particular emphasis on the materials needed in the electronics industry**
- **Biochemical separations techniques**
- **Preparation and properties of catalysts**
- **Flow of powders and granular materials**
- **Applied mathematics for chemists and chemical engineers, illustrating some of the newest mathematical techniques (presented in the style of the imaginative text by Marshall & Pigford [8])**
- **Stochastic processes in chemical engineering**

- Colloids, emulsions, and suspensions, taking into account hydrodynamic, chemical electrical, and surface phenomena
- Chemical kinetics and reactor operation laboratory manual
- Fuels and their combustion, making use of the newest results from kinetics and transport phenomena
- Applied physical chemistry for non-chemical engineers, including some of the "classical" topics that have vanished from physical chemistry textbooks
- Product development, giving case studies on methods that have been evolved for making products with specified shapes, sizes, optical properties, corrosion properties, etc.
- Two-phase flows of polymeric liquids
- Thermodynamics and phase equilibria of polymeric systems

Better lists can undoubtedly be prepared by those under thirty-five, for they are the ones who should be itching to reorganize the profession.

WHO SHOULD WRITE?

Not everyone is suited to be an author. The principal requirements for bookwriting are: (i)

It may be that industrial organizations will wish to assist in the teaching of chemical engineering by allocating funds specifically for the preparation of textbooks.

thorough knowledge of the subject, (ii) skill in the use of the language, (iii) a highly developed sense of organization, (iv) much enthusiasm for telling others about the subject, (v) enough of a sense of impatience to get the job done, (vi) ability to interact with coauthors, (vii) a willingness to attend to details, (viii) familiarity with the key people in the field, (ix) an attitude of innovation, (x) ability to evaluate critically the published literature in the field, (xi) a good sense of humor, (xii) excellent health and stamina.

Very few people have all these characteristics. Consequently most writing projects are undertaken by a small group of individuals who can pool their knowledge and talents and make up for each other's shortcomings. This brings to mind the limerick [9].

*When twins came their father Dan Dunn
Gave "Edward" as name to each son
When folks said "Absurd!"
He replied, "Ain't you heard
That two Eds are better than one?"*

No doubt about it—two heads (or even three or four) are better than one when it comes to producing a responsible manuscript. I've never gone

solo in the book-writing business, and it's always seemed to me that it would be a lonely chore. True, there have been moments when I've had disagreements with my coauthors and had second thoughts about the joys of cooperative efforts, but usually out of these disagreements have come a better understanding of the subject and consequently more lucid writing.

In chemical engineering we should have more teams of authors in which one author is from industry and one from academia. In this way a balance could be achieved between industrial practice on the one hand and academic research on the other.

WHEN TO WRITE

The time is ripe for an author to begin writing a book when he has a burning desire to communicate his subject to his readership. Without an intense feeling of "missionary zeal" (why do missionaries get singled out for this honor?) a person probably will not have the energy and drive needed to complete the manuscript in a reasonable time. But one must have more than this compelling wish to communicate to his professional colleagues. There must be some element of *novelty* in the projected manuscript. Just what kinds of novelty should be required?

Novel ideas. If one has spent 10 or 15 years doing research on some particular topic and has been particularly successful and productive, the time may have arrived for him to collect his cumulative findings in a monograph. Preparing a book gives him a chance to summarize new achievements and put them in perspective. And who else is better prepared to do this than the originator of the novel ideas?

Novel survey of recent research. In every field—and particularly in rapidly developing ones—it is very important to prepare from time to time authoritative, critical, reviews of the recent advances and current status. To be useful such a review should try to resolve current controversies, suggest new experiments, establish new organizing schemes for the subject material, and compare and contrast competing theories or methods. Such an activity requires research status in the field, thorough familiarity with the key participants in the subject area, and the ability to recognize novel viewpoints and imaginative organization.

Novel organization of old ideas. We need textbooks in every profession. Inevitably much of the material in most textbooks will already be well-known and widely accepted. The novelty here has to be in the improved pedagogy, imaginative problems, sparking new applications of old material, new viewpoints made possible by recent research advances, and more up-to-date data, apparatus, computing procedures, and materials. Even for old subjects, such

as thermodynamics and fluid dynamics, much can be done to create textbooks with a high degree of novelty.

The key words throughout are “novelty”, “creativity”, and “imagination”. If a prospective author is not in a position to contribute new, creative, and imaginative thoughts of some kind, it is not yet time to put pen to paper (or sit down at the keyboard of a word processor).

HOW TO GET READY TO WRITE

Before the actual writing process begins, there are certain preliminary matters which should be attended to if the writing is to proceed efficiently and if the final printed volume is to be sharply focused.

Establishment of Aim, Scope, and Level. Book-writing demands dedication to a single goal. At the very outset the authors should specify the audience for whom their book is intended and the scientific background that the audience will have. The purpose of the book should be carefully spelled out and the boundaries of the subject material should be agreed on. Keep in mind the German proverb “*In der Beschränkung zeigt sich der Meister*”. (The true master knows how to limit himself.)

Preparation of an Outline. Book-writing demands organization. A list of chapters should be prepared and then the section headings within each chapter should be agreed on. Every effort should be made to arrange the subject material in such a way that the *organization* of the material jumps out at the reader when he looks at the Table of Contents. One of the most important contributions of the authors is to provide the reader with a framework for the subject into which the details can gradually be filed away. Authors should spend a lot of time on arranging their table of contents and choosing the chapter titles in such a way that the reader understands the anatomy of the subject material.

Allocation of Time. Book-writing demands large blocks of *uninterrupted working time*. The writing should be done as quickly as possible in order that the authors maintain momentum and continuity of thought. If the writing is spread out over too long a period, much time and energy are frittered away in rereading and updating previous chapters.

Establishing a Place to Work. Book-writing demands *isolation*. It is very important to find a room in the library, a room at home, an abandoned store-room or any out-of-the-way place (preferably phone-less), where the book-writing activity can occur. All of one’s writing materials, reference books, dictionaries, reprints, and journals should be moved into this area away from the hurly-burly of everyday professional life. This may mean a common room where all coauthors work together, or it may mean separate rooms for each coauthor. In any case, this Shangri-La should be inviolate.

Suspension of Unnecessary Activities. Book-writing demands sacrifices of the authors, particularly in curtail-

ing or eliminating social activities, attendance at meetings, participation on committees, and time spent on hobbies. One simply has to *get one’s vectors lined up* so that for the book-writing period most of one’s energies are directed towards a single goal.

Establishment of a Style Sheet. Book-writing demands consistency. Much time can be saved if at the very outset the authors can agree on certain questions of *nomenclature, notation, and style* (by the latter we mean those picky little details such as whether you write Eq. 5.2-1, Eqn. (5.2-1), eq. [5.2-1], or (V(2).1)). One can get a lot of help by imitating the style of some book that one admires, or one can get valuable tips from the carefully prepared style manuals provided by the publisher.

After the index has been shipped off to the publisher, there is a several-month waiting period until the author finally gets the first copy of his new book. This period seems interminable . . . Most authors about this time experience a rather serious “post partum” depression.

Yes, book-writing demands a lot of preparation and commitment right from the beginning. Failure to get the writing done within a reasonable time span can result in an out-of-date manuscript or one that doesn’t have much coherence. Failure to establish a suitable place for writing can result in inefficient work habits, interruptions, and errors. Failure to establish a style sheet can result in a lot of rewriting and last-minute changes. Failure to establish the aims and to prepare an outline can result in chaos and confusion, and even ultimately the abandonment of the project. Many manuscripts have withered away and authors have become frustrated or embittered as a result of inadequate preparation.

HOW TO WRITE

The actual production of manuscript copy is a very personal matter. Each author has to develop his own *modus operandi*. Some like to have a daily goal of, say, four typed pages; others like to work for, say, three hours per day; still others like to work in spurts. Some like to work with pencil and yellow pad, using an eraser as they go; some scribble their thoughts on scratch paper and then type a neat manuscript from their rough notes; still others prefer to use a dictating machine; very rapidly word processors are replacing the pencil, pen and typewriter.

Regardless of the writing procedures that an author chooses to adopt, there are many points to keep in mind to insure quality of the finished product:

Bibliography. Those scholarly-looking footnotes at the bottom of the page are not put there as a show of erudition. They serve two purposes: to tell the reader where additional information may be found in the technical literature, and to thank originators of the ideas for their contributions. It is essential to maintain an accurate bibliography and to keep meticulous track of the sources of all material used. It is a source of lasting embarrassment if later on you find you have slighted a colleague by failing to acknowledge his contribution.

Orientation. It is vital to provide the reader frequently with introductory or concluding paragraphs that give him orientation and perspective. It is difficult enough to master the details of any technical subject, but it is even more difficult to understand the status, principal challenges, or limitations of the subject. It is also very valuable to supply generous cross-referencing within the book to help the reader understand how various topics are interrelated.

Equations. In presenting derivations it is, of course, essential that the equations be correct, and in the manuscript they should be written precisely in the form that they are to be typeset. But that is not enough. One should also group symbols in meaningful ways so as to suggest or emphasize the physical content and maintain the groupings carefully in a sequence of equations. The use of dimensionless ratios is particularly helpful. There is a lot of artistry involved in displaying derivations of equations; the equations can be remembered more easily and their physical meaning better understood if attention is paid to the arrangement of the mathematical symbols and if symbols are used that have mnemonic value. My mentor, Professor Jan de Boer at the University of Amsterdam, once cited the Dutch proverb *Set oog wil ook wat hebben* (the eye also wants to have a treat—i.e., it is not enough to have the equation correct, but it must also look artistic!).

Graphs, Charts, and Tables. Much engineering work involves the use of tabular or graphical summaries. Reliable, accurate, easy-to-use reference material is indispensable. Here again there is a lot of artistry involved in cramming as much as possible into a visual display that can give the reader a good overview of a lot of information.

Illustrative Examples and Problems. Professor Olaf A. Hougen said that if you can't make up good problems and illustrative examples for a topic, then that topic may not be worth teaching to students in an engineering course. Certainly one of the great strengths of the Hougen-Watson-Ragatz series was the imposing collection of worked and unworked problems. Carefully prepared illustrative examples are often more helpful to students than long discussions in the abstract. Also for industrial practitioners an illustrative example is extremely useful for self-instruction. One time when Professor Hougen was visiting a blast furnace on a plant trip with a group of undergraduates, he asked one of the engineers how they made computations for their plant; the engineer said that he had found an excellent book that told just how to do it—and then he produced a copy of Professor Hougen's own book on material and energy balances, which had an extensive illustrative example on blast furnaces! In writing text-

There's no need to inundate the reader with arcane incantations or sesquipedalian persiflage—(it) offends most engineering readers; furthermore we must remember that science and engineering are international and that the native language of a large percentage of the readers is not English.

books, my coauthors and I often found that we had to go back and change the main text or include some additional tables after trying to work out the details of our own problems and examples.

Solutions Manual. Most professors of engineering are overworked, and having a solutions manual for grading the homework assignments is enormously helpful. Also, as we all know, it not infrequently happens that a teacher is pressed into service for teaching some course in an area where his own background may be only minimal; a solutions manual can actually help to instruct the teacher. If the authors prepare the solutions manual right along with the textbook, they have the additional peace of mind that their problems actually can be worked and that the solutions are physically reasonable.

In every part of the manuscript preparation one very good motto is: *KEEP IT SIMPLE*. The learning of technical material is difficult, and the reader does not appreciate it when the author thoughtlessly or purposely introduces unnecessary complexities. Tables, notation, equations, graphs, bibliographical listings—all of these should be arranged as simply as possible. Simplicity in sentence structure and vocabulary is also highly desirable. There's no need to inundate the reader with arcane incantations or sesquipedalian persiflage—that kind of language offends most engineering readers; furthermore we must remember that science and engineering are international, and that the native language of a large percentage of the readers is not English. Making things simple for the reader demands a lot of effort by the author. It requires great talent and insight to distil out of the vast and conflicting literature the essential ideas on a given subject, but this is one of the obligations of authorship.

One bit of advice that cannot be overemphasized: allot some time for physical exercise and relaxation during the period you are working on a manuscript. During periods of intense mental activity, the mind sometimes gets 'clogged up'. I have found that a good long hike (preferably alone) once a week is essential to good book-writing. Five or six hours out-of-doors is worth far more than the same amount of time behind the typewriter. After one or two hours of walking, the mind begins to 'come unclogged', and ideas

about arrangement of material and detailed explanations begin to flow freely. I always take along a pen and a stack of 3 x 5 cards to jot down the ideas as they come. After a hike I come back to the manuscript physically relaxed and mentally aired out, and I usually have several cards full of new thoughts.

INTERACTIONS WITH THE PUBLISHER

My own dealings with publishers have been generally very cordial. Some of my colleagues have, however, had unpleasant experiences; these may in part have resulted from not recognizing what their relation to the publisher would be. Just what are some of the ways in which authors interact with publishers?

The Contract. Many authors are so delighted and flattered that someone is actually going to publish their manuscript that they really do not give the contract much thought. They should consider carefully not only the question of royalties (which can be computed in many different ways), but also such questions as the making of corrections in later printings, the choice of type fonts available, the format of the book, the form in which art work is to be delivered to the printer, the status of the book if it goes out of print, and the type of paper and binding to be used. It pays to discuss contracts with colleagues who have already published to find out what problems they may have had. Authors should remember that they are entering into a business agreement, and if the nature of the agreement is thoroughly understood the collaboration will be more harmonious. Most publishers have standard printed contracts, but authors should not hesitate to request modification of the wording where appropriate.

A Visit to the Publishing House. If possible one or more of the authors should visit the publisher's. Many of the editing and production problems are much more easily handled if the authors have met the key staff members of the publishing team. By seeing how various parts of the production are performed, authors can avoid making unreasonable demands on their publisher.

Manuscript Review. The publisher will normally send the manuscript to one or more experts in the field to elicit comments. This is very beneficial to the authors, and the reviewer's criticisms should be taken seriously. The authors should also get comments from colleagues or students. At the time we published *Transport Phenomena*, our publisher (John Wiley and Sons) prepared a "preliminary edition" which was used for two years by us at the University of Wisconsin and also by Professor J. E. Powers at the University of Oklahoma, Professor J. Dranoff at Northwestern University, Professor E. Weger at John Hopkins University, and Professor K. M. Watson at Illinois Institute of Technology. The advice that we received from them and their students was invaluable. The students' comments were often very blunt and vitriolic, but they had a sobering influence on the three of us. And

it was Professor K. M. Watson who suggested to us that the problems at the ends of the chapters ought to have a subscript to tell how difficult the problems were. With the word processors now available, it should be possible for authors to put out their own preliminary editions before sending a final manuscript to the publisher.

Copy Editing. Most authors hate the copy editors. These faceless people (unless you have actually visited them on their home ground) correct your grammar, turn your sentences around, and insert schoolmarmish queries in the margins. Adults just don't like to be treated that way. In the long run, I have profited from my interactions with the editors; they have a tough job to do, and authors should learn all they can from those "purple pencil people" who deface their cherished manuscript. One does, however, have to check all the purple marks very carefully to be sure that meanings are not changed and that correct equations are not transformed into gibberish.

Proofreading. Most authors regard this activity as extremely distasteful. It is a demanding, exhausting chore that cannot be turned over to wives, assistants, or students. This is the authors' last chance to be sure that errors have not been introduced by the editor or the printer; the authors may even find that some of their own errors have managed to survive to this stage. No matter how careful one is, a number of errors will nonetheless slip through. Some of these will be trivial misprints, and occasionally an erratum will be funny—such as the appearance of the word 'Bird' in Fig. 9.L on p. 305 of the first printing of *Transport Phenomena* [1] (all india ink drawings are marked with the name of the senior author, and in the final composition of this page the author's name was not whited out). Another amusing erratum is the appearance of the word "theological" in lieu of "rheological" in Dr. J. R. A. Pearson's book on polymer processing [10]. It's impossible to eliminate all errors, of course, but the authors have the responsibility to their future readers to do their level best.

The Index. By the time the authors have written the manuscript, done battle with the copy editor, and slaved over several sets of proofs, they are usually approaching a state of mental and physical ruin. It is at this time that they are asked to prepare the index, and this task is also one that cannot be delegated. There's the story about the arrogant professor who had just finished a 1200 page book on ornithology, and ordered his graduate students to prepare the index. The students, chafing under this assignment got revenge by inserting an entry: "Birds, for the, 1-1200". A number of otherwise excellent books have been seriously flawed by the authors' irresponsibility with regard to preparing an index.

I said at the outset that my own relations with the publishers have generally been very pleasant. I do recall, however, that I got rather upset with Mr. J. S. ("Stet") Barnes of John Wiley and Sons because he wouldn't let me put a Dutch proverb at the end of the preface of *Molecular Theory of Gases and Liquids* [1], since Dutch proverbs don't have much currency outside of The Netherlands. Of course he was right. But six

or seven years later, when writing the preface for *Transport Phenomena* [1] I decided to get even by including "secret messages" in the preface and postface of the book in the form of acronyms. When the book was published I was invited to attend a luncheon for the Wiley sales force to let them ask me some questions about the new book. At the end of the question-and-answer session I reminded Mr. Barnes of our earlier altercation regarding the Dutch proverb, and announced that I had at last succeeded in evening the score by including hidden messages. Mr. Barnes turned several colors of red, grabbed a copy of the book, and began deciphering the messages; he was visibly relieved to find that the messages were not directed at him personally or at the publisher.

PRE- AND POST-PUBLICATION EVENTS

After the index has been shipped off to the publisher, there is a several-month waiting period until the author finally gets the first copy of his new book. This period seems interminable. One has to start putting his life back together again and do all kinds of chores that had been put off. But the conscientious author begins to have nagging doubts as to whether he really left the reader with the correct impression in Chapter 6, and whether he should really have included Table III in Chapter 8, and whether a derivation couldn't have been presented more simply in Chapter 11. And perhaps he discovers to his horror that a key reference has been omitted in Chapter 9 or that a life-long friend and colleague was omitted in the acknowledgments. Most authors about this time experience a rather serious "post partum" depression.

The day that the first copy of the book arrives, there are feelings of elation, accomplishment, relief, and pride, but mingled with feelings of dissatisfaction, and these latter feelings usually are reinforced by the unwelcome discovery—on that first day—of several misprints or errors. This odd collection of emotions is known only to authors. But the period of depression is not yet over, because it will be six to twelve months before the book is reviewed in the professional journals. During this period of waiting the authors tend to magnify out of all proportion the errors that they find. In addition, as scientific and engineering research surges onward, the authors realize that their opus magnum is already getting out of date. It is very important for book-writers to be prepared for this stage of their lives; it's a good time

for the development of a new hobby, a trip to Tasmania, or planning the next book (before you do that, however, you should join your local chapter of "Authors Anonymous").

In the wake of the publication one does have to maintain a file of errata, unpleasant though this chore may be. Authors do appreciate it when readers take the time and trouble to write or phone them about mistakes that have been found, since these errors can be corrected in later printings. Also, many authors maintain lists of "corrigenda" (I think this word is somewhat more friendly than "errata"), which they duplicate and make available to other workers in the same field. So don't hesitate to write to authors and let them know how their books can be improved.

As a matter of fact, after you publish a book you have correspondence with all sorts of people all over the U.S. and abroad. I've had letters from students wanting topics for term papers, from people in industry asking for the solution to some problem at the end of a chapter in connection with a specific design problem, from students who claim that they were graded incorrectly on an exam problem by their teacher (and they want me to be the referee), from professors who don't like my notation or units, etc.

Since becoming an author I don't hesitate to write other authors when I feel shortchanged. During my first week of teaching at Kyoto University, I found it was impossible for me to get a ham sandwich without mustard at a nearby restaurant because I didn't know how to say 'without'; that word was not to be found in the grammar book [11] (by Professor S. E. Martin of Yale) I had been studying. Right away I wrote to Professor Martin, explained my dilemma, and sent him a list of errata I had found in his textbook. He responded promptly and kindly sent me a complimentary copy of the newest edition of his book. Several years later, when visiting the ChE Department at Yale, I went over to see Professor Martin. He greeted me immediately with "Ah, yes, you're the one who couldn't order a sandwich without mustard!" Don't be timid about writing to authors—they enjoy hearing from their customers.

Of all the emotional experiences after publishing a book, none can beat that crushed feeling you get when you see a copy of your book in the used-book section at the bookstore. Then you open it and see the underlined paragraphs, the penciled notes about exam dates in the front cover, and

the comments in the margins (perhaps even an occasional unkind remark about the authors). You realize then that some student tried to study your book and was turned off by the subject, or by your style of writing, or maybe because you as the author didn't somehow have that reader in mind. The time to think about that discouraged student is not after the book has been published, but while the manuscript is being prepared!

REWARDS

Book-writing should not be undertaken to gain fame and fortune. If you want to make a fortune you're better off to buy real estate, do consulting, or study the art of investing. Book-writing is no guarantee of fame, since one can damage one's name if the final product does not meet with the approval of the professional community. No, the rewards of book-writing are of a different nature.

First of all there is the opportunity for scholarly growth. By the time you have completed a book manuscript you have an extremely detailed and thorough knowledge of a subject. This in turn enriches your capabilities as a teacher, researcher, consultant, or designer. Also, having spent months in reading about many facets of the subject and having devoted months to organizing the material, you are in an excellent position to keep up with the burgeoning literature of the field. In addition, if your book has been well received, many people will send you reprints of their work and copies of their books just as a question of collegial courtesy, and this also makes it easier to keep abreast of the latest advances. Book-writing also makes you aware of the problems that most urgently need to be attacked in your field, and hence you are led into new research vistas.

The second reward of book-writing is the feeling of service to the professional community—and this is an international community. Considerable satisfaction results from knowing that one has produced a manual, a textbook, a monograph, or a handbook that will help other people to do their jobs better or to help them to acquire new knowledge.

And finally the third reward for book-writing is the learning from one's coauthors. I have been very fortunate to have collaborated with some truly extraordinary people. From *Joe Hirschfelder* I learned that science is just one thrilling adventure, and that numerical tables should never contain any errors. Every encounter with *Chuck Curtiss* has resulted in his patiently teaching me

some new technique from his seemingly infinite supply of theoretical tricks. *Warren Stewart*, who seems to have a photographic memory and total recall, introduced me to simultaneous heat-and-mass transfer with and without chemical reactions; his dedication to expository and numerical accuracy never ceases to amaze me. I have valued very much *Ed Lightfoot's* almost iconoclastic approach to science and engineering, which sometimes knocks you off balance and makes you think about subjects from a totally different point of view. *Bill Shetter* has helped me to appreciate Dutch literature and linguistics, and never to trust foreign-language dictionaries blindly. My colleagues *Ed Daub* and *Nob Inoue* taught me a lot about the subtleties of the Japanese language and the scholarly contributions of Japanese engineers and scientists. And my former students *Bob Armstrong* and *Ole Hassager* rejuvenated me by helping me to understand better some of the notions of modern continuum mechanics, rheology, and kinetic theory. All of these people were lots of fun to work with, and their constructive attitudes and great sense of humor made each publishing undertaking an adventure rather than an ordeal. Sure, we had our moments of misunderstandings and perhaps even a harsh word now and then, but the teamwork and camaraderie are what we remember. I treasure the memories of our joint ventures, and would like to thank all of my coauthors for enriching my professional and personal life. I know this may sound sentimental, but friendships forged in manuscript-writing and tempered by the galley-proof reading are very special.

ENCOURAGEMENT FOR BOOK-WRITING

Most book-writing is done nights and weekends by dedicated authors whose spirit of service is almost overpowering. It requires a lot of personal sacrifices. There are only limited possibilities for obtaining a grant of financial aid to write a book, and thereby have a substantial block of time for bookwriting. Guggenheim grants have been used for preparing research monographs, although chemical engineers do not seem to have made much use of them for this purpose. In chemistry, the George Fisher Baker Lectures of Cornell University have enabled outstanding scientists to give special lectures and prepare books; this series has been eminently successful with *Flory's Polymer Chemistry*, *Debye's Polar Molecules*, and *Pauling's Nature of the Chemical Bond* being a few of the trail-blazing volumes resulting from

this endowed chair. At the University of Wisconsin we have established the Olaf A. Hougen Professorship, patterned somewhat after the Baker Lectures, and we hope that the contributions of the Hougen Professors through the years to come will be influential in the future teaching and research in chemical engineering. Other universities ought to consider setting up similar endowed chairs to honor eminent authors and researchers.

It may be that industrial organizations will wish to assist in the teaching of chemical engineering by allocating funds specifically for the preparation of textbooks; this might be a useful alternative or supplement to the "young faculty grants", which have been very much appreciated by the universities. The American Institute of Engineers may want to reexamine its "Institute Lectureship" with an eye to encouraging the improvement of research and teaching in the U.S.; originally the Institute Lectureship Award carried with it the responsibility for preparing a monograph, published by AIChE, but it is my understanding that only several of the award winners have fulfilled that obligation. In the frenetic professional world of today, it is probably asking too much for the Institute Lecturer to prepare a monograph without providing some released time for undertaking the manuscript preparation.

Book-writing is not even encouraged in some institutions. I have heard of several chemical engineering departments in which young faculty are actively discouraged from undertaking any textbook writing by intimations that such an activity will in no way contribute to their chances for tenure. And our present system of research grants, with the continual scrambling for funds and requirement of continuity of productivity, almost prohibits an active researcher from taking a year or two off to write a first-rate book. Those who do have the temerity to do this risk losing their grants or their health or both.

BOOK-WRITING IN THE FUTURE

When Joe Hirschfelder, Chuck Curtiss, and I worked on the manuscript for *Molecular Theory of Gases and Liquids* [1], about thirty years ago, there were no Xerox machines, and manuscript copies had to be prepared using carbon paper. All equations had to be filled in by hand, and since we had no correction fluid at that time, erasers, and the inevitable smudges were just part of the book-writing scene.

In the near future the entire book-writing and book-publishing process will undergo an upheaval [14]. Manuscripts will routinely be prepared by word-processors, and publishers are already issuing instructions to prospective authors about the use of these devices [14]. Manuscripts will not be mailed to the publisher, but instead floppy disks and tapes will be sent. The copy editing will probably be done with word-processing equipment, and the page layout, pagination, indexing, preparation of drawings, checking of cross references, and other tedious chores will become automated and computerized. This will relieve a lot of the drudgery of book-writing and make it easier for the author to concentrate his efforts on the technical content of his book.

Publishers are still faced with several problems that are particularly difficult to solve. The first is the widespread use of copying devices to make copies of parts or all of books. And the second is the widespread publishing of unauthorized editions of books in other countries. It is the publisher, after all, who has to bear the cost of identifying manuscripts, reviewing of manuscripts, editing of manuscripts, preparation of artwork, page layout, typesetting, advertising and paying royalties to the authors. When large scale photocopying occurs it clearly upsets the economics of the industry and neither the author nor publisher are properly remunerated for their labors.

CONCLUSIONS

Let us now return to the Biblical quotation at the beginning: ". . . of making books there is no end . . .". Although the methods for preparing manuscripts and producing books will undergo tremendous changes in the next decade, the need for books is still going to be present. If young people in our profession are going to be trained at our institutions of higher learning, we must have lively, up-to-date, and responsibly written textbooks. As Carlyle said: THE TRUE UNIVERSITY OF THESE DAYS IS A COLLECTION OF BOOKS, and it is no wonder that these words are found engraved over the portals of many university libraries. The industrial practitioners also need source books on chemical engineering. As Dr. Thomas H. Chilton (of the Engineering Department of DuPont) said [2], ". . . there must be more books, for engineering data and the interpretation of results are fundamental needs. The industry grows not only on

transmitted art and practice, but also through the careful and long study and reinterpretation of described practices, art, and data.”

The field of chemical engineering will inevitably be known and measured by its journals and books. It behooves us, as professionals, to offer encouragement to willing and responsible book authors and to strive for the amelioration of the conditions under which these books are prepared. The establishment of special book-writing chairs at universities, an annual AIChE supported monograph, and industrial sponsorship for certain kinds of books could profoundly influence the direction and speed of progress in the profession of chemical engineering.

In conclusion I would like to say a few words about “style” in book-writing—“style” in the general sense of the word. In a recent issue of the *Wall Street Journal* [15], there was an article by James Sloan Allen on the subject of style, particularly with regard to the performing arts. But his comments apply also to book-writing, teaching, and research. He says that by style he means “that near-magical touch of artful individuality that elevates most anything one does above the routine, the common, or even the respectable. . . . There is more to style than well-wrought appearances. For there must be something within the performer, some attributes of character, that makes style possible. These attributes are imagination and will or discipline.” The books that lead chemical engineering into the future will be those imaginative and innovative volumes written by self-disciplined, responsible authors. □

ACKNOWLEDGMENTS

I am very much indebted to my departmental colleagues who have through the years given me considerable encouragement in my activities as an author, and also to my publishers (John Wiley and Sons, Martinus Nijhoff, and The University of Wisconsin and University of Tokyo Presses) for teaching me about the art and business of book publishing. I should like also to express my sincere appreciation to the Vilas Trust Fund of the University of Wisconsin whose financial support has been of great assistance to me in providing released time for the preparation of the manuscripts for my last three books. Finally I should like to acknowledge correspondence with Mr. Charles B. Stoll, Mr. Merrill G. Floyd, and Mr. Robert B. Polhemus of John Wiley and Sons, Inc., and with Dr. Dominic Sherony of the Xerox

Corporation, in connection with providing me material on the emerging methods in the publishing and printing industries.

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INTERSTATE RIVALRY

Continued from page 183.

year, the remaining four courses are taught for the most part in alternate years and reflect the research interests of individual faculty members. Thus UI teaches courses in biochemical engineering, mass transport and plant design while WSU concentrates on digital process control, extractive metallurgy and polymer reactor engineering.

Trial and Error

As with any attempt at innovation, unanticipated problems arise. We dealt with these in the time-honored engineering methodology of trial and error. As mentioned, our first attempt at solving the scheduling conflict was to teach on a compressed schedule to avoid the semester "overlap" period. Whereas this had worked for one class in the spring of 1981, it posed too great a burden when students were taking more than one course. The eventual solution was to start the fall semester on Idaho's schedule (early start) and the spring semester on WSU's schedule (February start). This approach leaves about six weeks between semesters (including Christmas break), a time when graduate students can devote efficient time to their research projects. The ultimate solution for us is that WSU will switch to an early start calendar commencing August 1984.

Another problem that had to be dealt with was the deliverance of students from one institution to classrooms at the other. We started off by using university vehicles, then we experimented with a 2-way microwave video link (see Table I); for the present we have settled on car pooling. To minimize transportation time, all graduate classes on the same campus are taught one following the other, and we teach three credit courses twice per week (1½ hour lectures). UI offers its classes Tuesday/Thursday afternoon, and WSU offers its classes Monday/Wednesday afternoon. Scheduling these blocks of time is flexible to meet the needs of the two programs and to interface with the undergraduate program.

The use of the microwave link is very time efficient and has a great deal of potential. However, both students and faculty were resistant to its use and we have temporarily discontinued this approach. Both universities are upgrading their microwave systems and it is likely that we will try it again once these modifications are in place. We also learned that intensive analyses courses such as "Chemical Engineering Analysis

I" are not well suited to this type of program. This course requires a great deal of independent student effort using computer simulation techniques. As a result, most of the instruction is tutorial in nature and, beginning Fall 1983, both departments will offer this course independently. For one professor to keep two computer systems happy was just too much work. Requiring students to become familiar with a different operating system also seemed inappropriate, not to mention the problems to be faced gaining computer access.

ADDITIONAL COOPERATIVE VENTURES

Not only has this program achieved the objectives of being able to offer broad based graduate courses while maintaining acceptable teaching loads, other cooperative ventures have arisen as well. An obvious extension is the joint sponsorship of visiting seminar speakers. Each department maintains a separate graduate seminar series with speakers often participating in both series. In addition, we join forces to sponsor at least one speaker per semester. We are able to attract (and compensate) many visitors by this method that we otherwise could not bring to our campus. The two departments take turns choosing the speakers in alternate semesters and visitors spend one day on each campus. Joint research efforts are another extension; a research program in food processing is currently being developed since it is a subject area of regional interest and combines the complementary talents of two faculty members. We have even had one student complete his coursework at one institution and conduct his research under the supervision of a faculty member at the other. Though this relationship between professor and student is not expected to be a common occurrence, it does illustrate the degree of flexibility and responsiveness that can result from a cooperative program between universities. □

CLEANING UP

Continued from page 173.

simulate the use of a chemical decontaminant to neutralize a contaminant, otherwise trapped, within the cavity. This work has already been published [7].

Parallel to these theoretical endeavors, an experimental program is in progress. Fig. 7 suggests the type of studies underway. A large (one centimeter) rectangular cavity is created in a flat plate, and can be filled with a liquid, containing a dye,

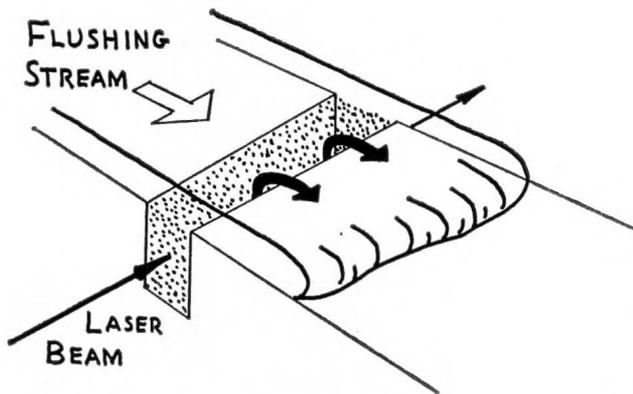


FIGURE 7. Experiment for study of removal of fluid from a cavity by an external stream.

that simulates a trapped contaminant. An external flushing flow is then initiated, which induces circulation within the cavity. A laser light shines down the cavity axis, and is received at the far end of the cavity. The intensity of the transmitted light is related to the amount of dye remaining in the cavity. In this way it is possible to measure the rate of removal of the contaminant, as a function of external flowrate, cavity geometry (aspect ratio), and viscosity of the trapped liquid.

This dual approach to research, in which theoretical and experimental studies proceed simultaneously, **but interactively**, is characteristic of our philosophy of research, and is proving to be quite successful.

Space does not permit a more complete discussion of our research program in this field. Suffice it to say that we are pursuing many of the questions raised in the discussion above, and that we anticipate that we will continue to carry on research in this field for some time to come. □

ACKNOWLEDGEMENT

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SURFACE PHENOMENA

Continued from page 169.

difference is that now we are accounting for the charged species rather than any species at the surface). The indirect mass balance and the indirect thermodynamic approaches (the Lippman equation) provide nice parallels between the two subjects. Details are given of the modelling of the electrochemical double layer with the emphasis on the effect of the variables, especially the potential determining ions, the indifferent electrolyte and the valence of the indifferent electrolyte on the double layer. The case problem is discussed and the emphasis then shifts to the DLVO theory which combines the material from Unit 6 with that of the current unit to yield the energy interaction curves. The dynamics of the stability of dispersions is discussed in the context of the von Smoluchowski equation for rapid coagulation and the use of the retardation factor, W , to account for slow coagulation. Models are also developed for orthokinetic coagulation. This section concludes with the design procedures for coagulation basins. Examples are worked for the case of coagulation of SBR latex and polystyrene latex. Other examples illustrated include ion exchange, froth flotation, electrostatic charging through pumping, deep bed filtration and corrosion product deposition in cooling circuits.

In the final unit in this course the stated case problem is to select a protective colloid (namely a polymer) that can be used in the suspension polymerization of PVC. This topic requires that we understand not only the adsorption of polymers to a surface but the configuration of the polymers once they are absorbed into the surface. The calculations introduced focus on the volume restriction and osmotic repulsion that occur when two surfaces containing polymers approach each other. This discussion of steric stabilization focuses mostly on suspension polymerization ap-

plications, although it could be used and extended to other topics.

This course has evolved over the past 10 years and has taken on more and more of the practical application flavour as data become available and as examples of the application are worked out. At the present time the course is offered both as a graduate course and as a technical elective for seniors. We find that the attractive features of this course are the practical applications, the demonstrations that can be given in class to illustrate the behaviour, and the research films that have been developed to illustrate the behaviour. □

REVIEW: REACTOR DESIGN

Continued from page 176.

good qualitative discussion of the many problems related to reactor analysis and design.

The book is divided into two parts. The first part, containing six chapters, is on Chemical Engineering Kinetics. The second part has eight chapters, and deals with the Analysis and Design of Chemical Reactors.

In the kinetics part, the first chapter is on homogeneous reaction kinetics, while the second deals with kinetics of heterogeneous catalytic reactions. In Chapter 2, the treatment of how Langmuir-Hinshelwood Hougen-Watson rate equations are derived, given a reaction mechanism, is presented well. Both chapters also contain methods for kinetic parameter estimation, which are usually not found in most texts. Chapter 3 is the longest one in the first part, and it treats the interaction of transport processes with reaction kinetics in a single catalyst pellet—essentially the effectiveness factor problem. It is a good and thorough chapter. Chapter 4 has a good account of gas-solid noncatalytic reactions. Catalyst deactivation, by poisoning and coking, is treated in Chapter 5. Gas-liquid reactions are covered in Chapter 6, where both the film and surface renewal models are discussed.

The second part of the book starts out with a short Chapter 7 on transport equations for reactors. The next three chapters treat the batch, plug-flow, and stirred-tank reactors, respectively. Chapter 11, on fixed-bed reactors, is the longest (130 pages) in the book, and is indeed comprehensive. One and two-dimensional pseudohomogeneous and heterogeneous models are discussed in detail, and correlations to estimate transport parameters for these models are also given.

Chapter 12 deals with non-ideal flow patterns, and also has a description of the more fundamental population balance models. Chapters 13 and 14 discuss the modeling of fluid-bed and multiphase reactors, respectively.

The collection of topics in the book is broader than in most other books available in the reaction engineering area, and this is a genuine strength. Nevertheless, there are omissions, some of which may also be cited. These include thermodynamics of chemical reactions (a weakness also in several other books in the area); experimental methods for measuring transport properties in pellets, and a comparison of measurements with predictions of several models that are discussed; metal catalyst deactivation by sintering. In a book of this type, it would have also been nice to see, at least for CSTRs, a more thorough treatment of steady state multiplicity for single and complex reactions, and of the complexities of transient behavior that are possible—but, of course, not everyone shares the same hobbies.

The preface suggests that the book can be used at both the undergraduate and graduate levels. However, in view of the general level and extent of treatment, I expect that it is appropriate and more likely to be used as a graduate text. Those engaged in practice will also find this to be a useful source of principles and design information, and with the extensive references provided, an excellent introduction to the research literature.

There are some 112 problems given at the end of chapters, and a solutions manual is available. □

SELECTED NUMERICAL METHODS AND COMPUTER PROGRAMS FOR CHEMICAL ENGINEERS

*By Huan-Yang Chang, Ira Earl Over
Sterling Swift Publishing Co.
Manchara, Texas 78562*

**Reviewed by
Charles A. Walker
Yale University**

Introductory courses in computer programming necessarily emphasize methods that are available for solving general classes of problems without going into detail on the applications of these methods to the subject matter of specific disciplines. Since students of any discipline usually study computer programming at the same time that they are being introduced to the fundamental

concepts and methodologies of a discipline, they are not prepared to imagine how the solution of nonlinear equations (for example) might apply to their discipline. The authors have recognized that interest in computer programming for students of chemical engineering might be enhanced if they could see how the solutions of general classes of problems developed in computer science courses apply to chemical engineering. Their book might be useful for supplementary reading in a course on computer programming, although it is more likely to be useful for independent study by students in their junior and senior years, or perhaps for a short course offered in a chemical engineering department.

The book is at a very elementary level in terms of both computer programming and chemical engineering. The authors discuss briefly each of several general classes of problems and present computer programs (in FORTRAN Extended Version IV) for specific problems in chemical engineering. The first chapter, on the solution of nonlinear equations, for example, includes applications such as solving the virial equation of state, bubble-point and dew-point calculations, and simple flash vaporization. Other chapters deal with simultaneous linear equations, curve fitting, numerical integration and differentiation, linear interpretation, nonlinear simultaneous equations, and plotting. □

LETTER: Dead States

Continued from page 161.

Chemical Availabilities." This choice of reference state is simple and is compatible with the existing chemical literature, in particular, data on standard free energies of formation. More complex or idiosyncratic reference states defined by European thermodynamicists [2, 3, 5] have been adopted by some U.S. authors [4].

The motivation for these complex reference states appears to be the belief that one needs to and can calculate an absolute or "actual" availability, if the "dead" state of the environment is defined. The "dead" state definition consists of a careful description of the temperature, pressure, and composition of the environment. Once a system's components match this state, the system is "dead" as far as work production is concerned.

The effort to define a "dead" state has yielded a laborious analysis of the average composition of the hydrosphere, atmosphere, and lithosphere to crustal depths [5], and atmospheric "dead" states like that reprinted in the review, wherein the at-

mosphere is at 100% humidity, giving the actual atmosphere a negative availability, in most places for most of the year; and where the reference state for CO₂ requires that tabulated CO₂ free energy must be corrected for the work that may, in theory but not in practice, be obtained by expanding CO₂ from one atmosphere to an assigned atmospheric partial pressure.

There is less utility in computing an "absolute" or "actual" availability, than in computing an absolute energy. The calculation of the former should be done, according to Gibbs, with respect to the "surrounding medium," that is the interacting, local, environment; which is, of course, so dynamic that it is the universal subject of conversation.

Availabilities like energies have relative magnitudes, computed with respect to reference states. A reference state, is a reference state, is a reference state, and *not* a "dead" state. If it is dead now it will quicken as soon as Summer ends ($T_0 = 25^\circ\text{C}$) and the fog lifts ($p_{\text{H}_2\text{O}} = .03 \text{ atm}$).

Sincerely,
Martin V. Sussman
Tufts University

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- "Dust Explosions," Jean Cross, Donald Farrer; Plenum Publishing Corp., New York 10013; 248 pages, \$37.50 (1982)



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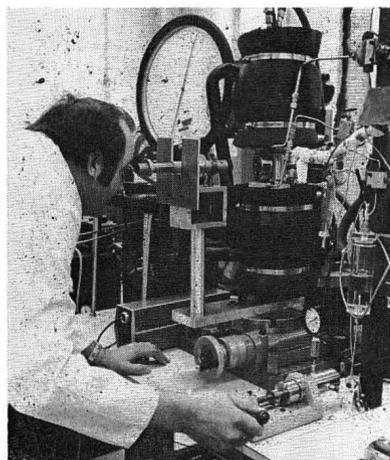
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Boundary Layer Theory, Pharmacokinetics, Fluid Mechanics and Mass Transfer in The Microcirculation, Biorheology

SIMON P. HANSON, Asst. Professor
Sc.D., Massachusetts Inst. Technology, 1982
Coupled Transport Phenomena in Heterogeneous Systems, Combustion and Fuel Technology, Pollutant Emissions, Separation Processes, Applied Mathematics

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

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

FARHANG SHADMAN, Assoc. Professor
Ph.D., University of California-Berkeley, 1972
Reaction Engineering, Kinetics, Catalysis

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

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

Tucson has an excellent climate and many recreational opportunities. It is a growing, modern city of 450,000 that retains much of the old Southwestern atmosphere.

For further information,
write to:

Dr. T. W. Peterson
Graduate Study Committee
Department of
Chemical Engineering
University of Arizona
Tucson, Arizona 85721

The University of Arizona is an
equal opportunity educational
institution/equal opportunity employer





ASU

ARIZONA STATE UNIVERSITY

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ENGINEERING DESIGN • PROCESS CONTROL •

Our excellent facilities for research and teaching are complemented by a highly-respected faculty:

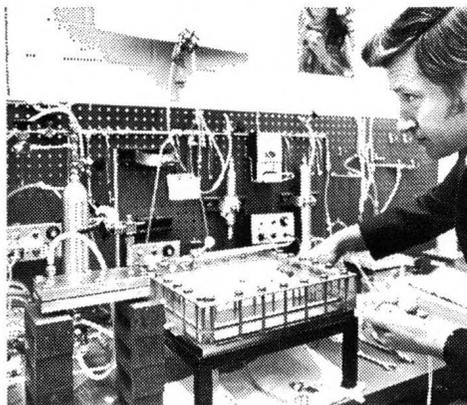
James R. Beckman, University of Arizona, 1976
Lynn Bellamy, Tulane University, 1966
Neil S. Berman, University of Texas, 1962
Llewellan W. Bezanson, Clarkson College, 1983
Timothy S. Cale, University of Houston, 1980
William J. Crowe, University of Florida, 1969 (Adjunct)
William J. Dorson, Jr., University of Cincinnati, 1967
R. Leighton Fisk, MD, University of Alberta, Canada, 1972
K. Kumar Gidwani, New York University, 1978 (Adjunct)
Eric J. Guilbeau, Louisiana Tech University, 1971
James T. Kuester, Texas A&M University, 1970
Kim L. Nelson, University of Delaware, 1983
Castle O. Reiser, University of Wisconsin, 1945 (Emeritus)
Vernon E. Sater, Illinois Institute of Technology, 1963
Robert S. Torrest, University of Minnesota, 1967
Bruce C. Towe, Pennsylvania State University, 1978
Imre Zwiebel, Yale University, 1961

Fellowships and teaching and research assistantships are available to qualified applicants.

ASU is in Tempe, a city of 120,000, part of the greater Phoenix metropolitan area. More than 38,000 students are enrolled in ASU's ten colleges; 10,000 of whom are in graduate study. Arizona's year-round climate and scenic attractions add to ASU's own cultural and recreational facilities.

FOR INFORMATION, CONTACT:

Imre Zwiebel, Chairman,
Department of Chemical and Bio Engineering
Arizona State University, Tempe, AZ 85287



CHEMICAL ENGINEERING GRADUATE STUDIES



THE PROGRAM

The Department is one of the fastest growing in the Southeast and offers degrees at the M.S. and Ph.D. levels. Research emphasizes both experimental and theoretical work in areas of national interest, with modern research equipment available for most all types of studies. Generous financial assistance is available to qualified students.

THE LOCALE

Auburn University has 19,000 students and is located midway between Atlanta, GA, and Montgomery, AL. Situated in a beautiful wooded setting, the local population numbers about 75,000 and supports good shopping and entertainment facilities. The University also sponsors many types of artistic, dramatic, cultural and sporting events. The combination of good weather and pleasant surroundings make outdoor activities such as hiking, boating, fishing and camping particularly enjoyable.

THE FACULTY

Robert P. Chambers (University of California, 1965) Enzymatic and Biomedical Engineering, Biomass Conversion, Adsorption and Ion Exchange.

Christine W. Curtis (Florida State University, 1976) Analytical Methods, Coal Chemistry and Liquefaction, Catalysis of Hydrocarbon Residuals.

James A. Guin (University of Texas, 1970) Coal Liquefaction, Catalytic Hydrotreating, Reactor Design, Heat and Mass Transfer.

Leo J. Hirth (University of Texas, 1958) Process and Plant Design, Economics, Oil Reprocessing.

Andrew C. T. Hsu (University of Pennsylvania, 1953) Thermodynamics, Solar Energy, Nucleation and Crystallization Kinetics.

Y. Y. Lee (Iowa State University, 1972) Biochemical Engineering, Reaction Engineering of Bio-Systems, Biomass Conversion

Timothy D. Placek (University of Kentucky, 1978) Environmental Pollution, Process Simulation, Multi-phase Transport Phenomena.

A. R. Tarrer (Purdue University, 1973) Coal Liquefaction, Oil Reprocessing, Solid-Liquid Separations.

Bruce J. Tatarchuk (University of Wisconsin, 1981) Heterogeneous Catalysis, Reaction Kinetics, Spectroscopic Characterization of Catalyst Materials.

Donald L. Vives (Columbia University, 1949) Oil Reprocessing, Vapor-Liquid Equilibria, Heat Transfer.

Dennis C. Williams (Princeton University, 1980) Process Dynamics and Control, Reactor Engineering.

RESEARCH AREAS

Biomedical/Biochemical Engineering

Biomass Conversion

Coal Conversion

Environmental Pollution

Heterogeneous Catalysis

Oil Reprocessing

Process Design and Control

Process Simulation

Reaction Engineering

Reaction Kinetics

Separations

Surface Science

Transport Phenomena

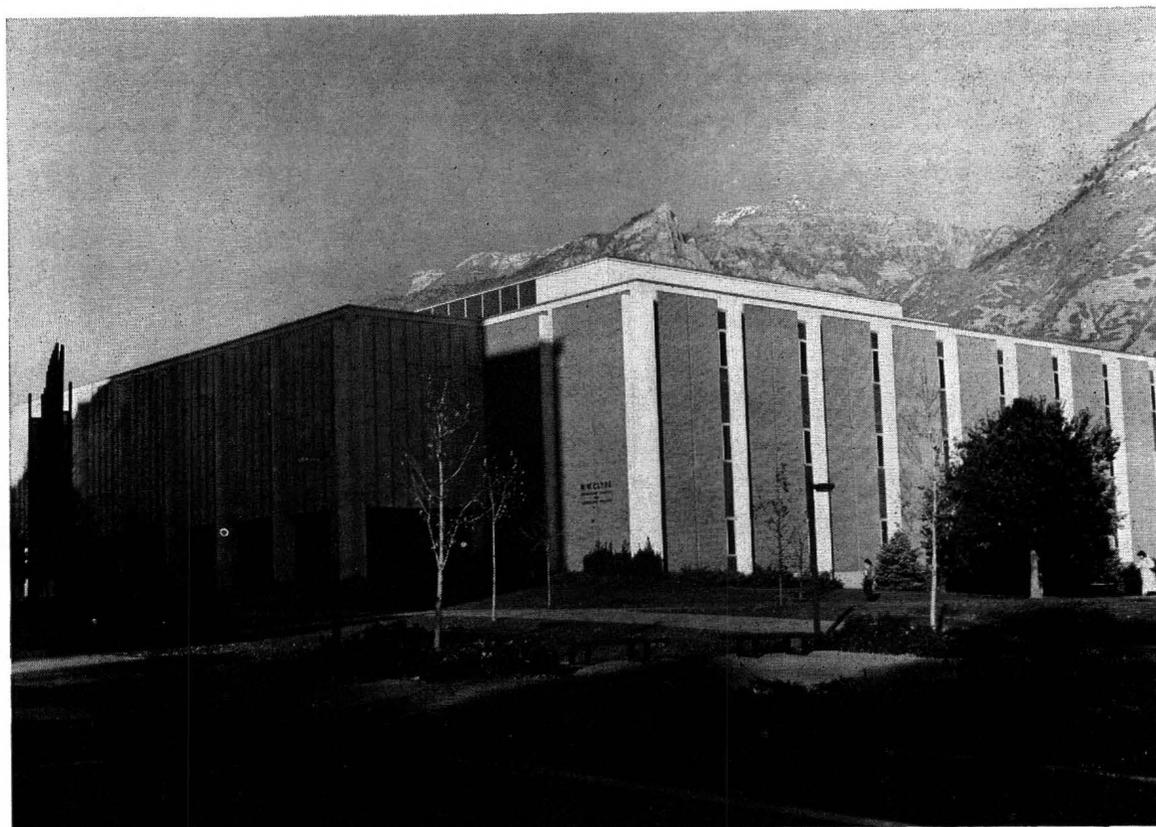
Thermodynamics

For financial aid and admission application forms write:

**Dr. R.P. Chambers, Head
Chemical Engineering
Auburn University, AL 36849**

BRIGHAM YOUNG UNIVERSITY

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- **Research Programs**

Biomedical Engineering
Catalysis
Coal Gasification

Combustion
Electrochemical Engineering
Fluid Mechanics

Fossil Fuels Recovery
Thermochemistry &
Calorimetry

- **Faculty**

D. H. Barker, (Ph.D., Utah, 1951)
C. H. Bartholomew, (Ph.D., Stanford, 1972)
M. W. Beckstead, (Ph.D., Utah, 1965)
D. N. Bennion, (Ph.D., Berkeley, 1964)
B. S. Brewster, (Ph.D., Utah, 1979)
J. J. Christensen, (Ph.D., Carnegie Inst. Tech, 1958)
R. W. Hanks, (Ph.D., Utah, 1961)

W. C. Hecker, (Ph.D., U.C. Berkeley, 1982)
P. O. Hedman, (Ph.D., BYU, 1973)
J. L. Oscarson, (Ph.D., Michigan, 1982)
R. L. Rowley, (Ph.D., Michigan State, 1978)
P. J. Smith, (Ph.D., BYU, 1979)
L. D. Smoot, (Ph.D., Washington, 1960)
K. A. Solen, (Ph.D., Wisconsin, 1974)

- **Beautiful campus located in the rugged Rocky Mountains**
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**Address Inquiries to: Brigham Young University, Dr. Richard W. Hanks, Chairman
Chemical Engineering Dept. 350 CB Provo, Utah 84602**



CHEMICAL AND PETROLEUM ENGINEERING

Program of Study

Degrees Offered

Master of Science
Master of Engineering
Doctor of Philosophy

Both the M.Sc. and Ph.D. programs are on the full-time basis and have residency requirements. Course work and a research thesis based on an original investigation are required of each student enrolled in either degree program. The M.Eng. involves part-time study. It is designed for those individuals working in the industry who would like to enhance their technical education. The M.Eng. thesis is usually on a design oriented project related to current or anticipated industrial trends. All the programs are designed to meet the specific interests and individual needs of the student. The research and computing facilities within the department and the faculty of engineering are excellent and continuously being upgraded.

Generous fellowships and assistantships are available throughout the calendar year to qualified applicants. The four month summer months are usually devoted to active research. Supplementary financial support may also be available from the research grants of the individual faculty members.

Research Areas

Thermodynamics—Phase Equilibria
Mass Transfer and Fluid Mechanics
Heat Transfer and Cryogenics
Kinetics and Combustion
Reaction Engineering and Process Control
Flow in Porous Media
Multi-phase Flows in Pipelines
Computer Aided Design of Pipe Networks
Fluidization
Environmental Engineering
In-situ Recovery of Bitumen and Heavy Oils
Natural Gas Processing and Gas Hydrates
Biorheology and Biochemical Engineering
Reverse Osmosis and Ultra Filtration

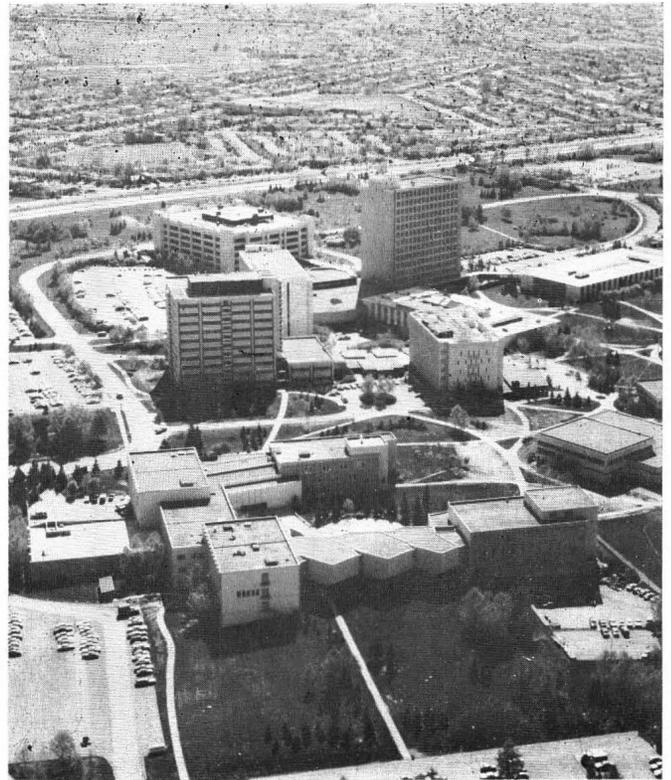
The Community

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

Applications

For further information and application material write to:

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



Faculty

R. A. HEIDEMANN, Professor and Head D.Sc. (Wash. U.)
A. BADAQSHAN, Professor Ph.D. (Birm.)
L. A. BEHIE, Assoc. Professor Ph.D. (W. Ont.)
D. W. BENNION, Professor Ph.D. (Penn. St.)
P. R. BISHNOI, Professor Ph.D. (Alta.)
M. FOGARASI, Sr. Instructor B.Sc. (Alta.)
G. A. GREGORY, Professor Ph.D. (Waterloo)
M. A. HASTAOGLU, Asst. Professor Ph.D. (SUNY)
J. J. HAVLENA, Sr. Instructor D. Sc. (Czech.)
A. A. JEJE, Assoc. Professor Ph.D. (MIT)
N. G. MCDUFFIE, Assoc. Professor Ph.D. (Texas)
A. K. MEHROTRA, Asst. Professor Ph.D. (Calgary)
M. F. MOHTADI, Professor Ph.D. (Birm.)
R. G. MOORE, Professor Ph.D. (Alta.)
P. M. SIGMUND, Assoc. Professor Ph.D. (Texas)
P. M. STANISLAV, Professor Ph.D. (Prague)
W. Y. SVRCEK, Professor Ph.D. (Alta.)
E. L. TOLLEFSON, Professor Ph.D. (Tor.)

THE UNIVERSITY OF CALIFORNIA,

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... offers graduate programs leading to the Master of Science and Doctor of Philosophy. Both programs involve joint faculty-student research as well as courses and seminars within and outside the department. Students have the opportunity to take part in the many cultural offerings of the San Francisco Bay Area, and the recreational activities of California's northern coast and mountains.

RESEARCH INTERESTS

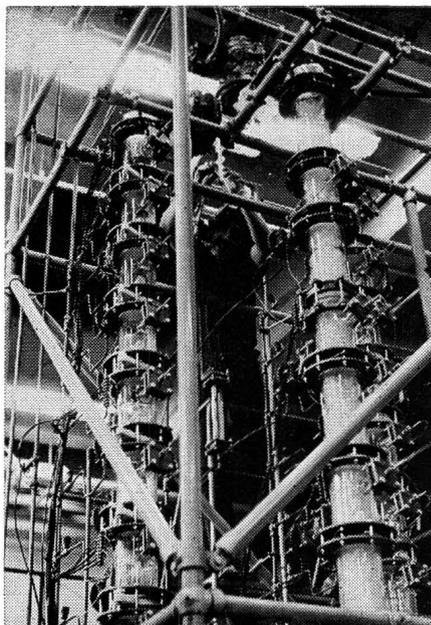
ENERGY UTILIZATION
ENVIRONMENTAL PROTECTION
KINETICS AND CATALYSIS
THERMODYNAMICS
POLYMER TECHNOLOGY
ELECTROCHEMICAL ENGINEERING
PROCESS DESIGN AND DEVELOPMENT
SURFACE AND COLLOID SCIENCE
BIOCHEMICAL ENGINEERING
SEPARATION PROCESSES
FLUID MECHANICS AND RHEOLOGY
ELECTRONIC MATERIALS PROCESSING

FACULTY

Alexis T. Bell (Chairman)
Harvey W. Blanch
Elton J. Cairns
Morton M. Denn
Alan S. Foss
Simon L. Goren
Edward A. Grens
Donald N. Hanson
Dennis W. Hess
C. Judson King
Scott Lynn
James N. Michaels
John S. Newman
Eugene E. Petersen
John M. Prausnitz
Clayton J. Radke
Jeffrey A. Reimer
David S. Soong
Charles W. Tobias
Theodore Vermeulen
Charles R. Wilke
Michael C. Williams

PLEASE WRITE: Department of Chemical Engineering
UNIVERSITY OF CALIFORNIA
Berkeley, California 94720

UNIVERSITY OF CALIFORNIA DAVIS



Course Areas

Applied Kinetics and Reactor Design
Applied Mathematics
Biomedical, Biochemical Engineering
Catalysis
Fluid Mechanics
Heat Transfer
Mass Transfer
Process Dynamics
Separation Processes
Thermodynamics
Transport Processes in Porous Media

Program

UC Davis, with 19,000 students, is one of the major campuses of the University of California system and has developed great strength in many areas of the biological and physical sciences. The Department of Chemical Engineering emphasizes research and a program of fundamental graduate courses in a wide variety of fields of interest to chemical engineers. In addition, the department can draw upon the expertise of faculty in other areas in order to design individual programs to meet the specific interests and needs of a student, even at the M.S. level. This is done routinely in the areas of environmental engineering, food engineering, biochemical engineering and biomedical engineering.

Excellent laboratories, computation center and electronic and mechanical shop facilities are available. Fellowships, Teaching Assistantships and Research Assistantships (all providing additional summer support if desired) are available to qualified applicants.

Degrees Offered

Master of Science
Doctor of Philosophy

Faculty

RICHARD L. BELL, University of Washington
Mass Transfer, Biomedical Applications
ROGER B. BOULTON, University of Melbourne
Enology, Fermentation, Filtration, Process Control
BRIAN G. HIGGINS, University of Minnesota
Fluid Mechanics, Coating Flows, Interfacial Phenomena, Fiber Processes and Refining
ALAN P. JACKMAN, University of Minnesota
Environmental Engineering, Transport Phenomena
BEN J. McCOY, University of Minnesota
Separation and Transport Processes
DAVID F. OLLIS, Stanford University
Catalysis, Biochemical Engineering
DEWEY D. Y. RYU, Massachusetts Inst. of Technology
Biochemical Engineering, Fermentation
JOE M. SMITH, Massachusetts Institute of Technology
Applied Kinetics and Reactor Design
PIETER STROEVE, Massachusetts Institute of Technology
Mass Transfer, Colloids
STEPHEN WHITAKER, University of Delaware
Fluid Mechanics, Interfacial Phenomena, Transport Processes in Porous Media

Davis and Vicinity

The campus is a 20-minute drive from Sacramento and just over an hour away from the San Francisco Bay area. Outdoor sports enthusiasts can enjoy water sports at nearby Lake Berryessa, skiing and other alpine activities in the Sierra (2 hours from Davis). These recreational opportunities combine with the friendly informal spirit of the Davis campus to make it a pleasant place in which to live and study.

Married student housing, at reasonable cost, is located on campus. Both furnished and unfurnished one- and two-bedroom apartments are available. The town of Davis (population 36,000) is adjacent to the campus, and within easy walking or cycling distance.

For further details on graduate study at Davis, please write to:

**Graduate Advisor
Chemical Engineering Department
University of California
Davis, California 95616
or call (916) 752-0400**

CHEMICAL ENGINEERING

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ALIFORNIA

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NGELES

PROGRAMS

UCLA's Chemical Engineering Department maintains academic excellence in its graduate programs by offering diversity in both curriculum and research opportunities. The department's continual growth is demonstrated by the newly established Institute for Medical Engineering and the National Center for Intermedia Transport Research, adding to the already wide spectrum of research activities.

Fellowships are available for outstanding applicants. A fellowship includes a waiver of tuition and fees plus a stipend.

Located five miles from the Pacific Coast, UCLA's expansive 417 acre campus extends from Bel Air to Westwood Village. Students have access to the highly regarded sciences programs and to a variety of experiences in theatre, music, art and sports on campus.

CONTACT

Admissions Officer
Chemical Engineering Department
5405 Boelter Hall
UCLA
Los Angeles, CA 90024

FACULTY

D. T. Allen
Yoram Cohen
S. Fathi-Afshar
T.H.K. Frederking
S.K. Friedlander
E.L. Knuth

Ken Nobe
L.B. Robinson
O.I. Smith
W.D. Van Vorst
V.L. Vilker
A.R. Wazzan
F.E. Yates

RESEARCH AREAS

Thermodynamics and Cryogenics
Reverse Osmosis and Membrane Transport
Process Design and Systems Analysis
Polymer Processing and Rheology
Mass Transfer and Fluid Mechanics
Kinetics, Combustion and Catalysis
Electrochemistry and Corrosion
Biochemical and Biomedical Engineering
Aerosol and Environmental Engineering

Graduate Study and Research in Chemical Engineering



University of
California,
San Diego

The University of California, San Diego

The University of California, San Diego, is located in La Jolla, near the northern limits of the city of San Diego. The thousand-acre campus site spreads from the seashore, home of UCSD's Scripps Institution of Oceanography, across a large portion of the adjacent Torrey Pines Mesa, high above the Pacific Ocean. Much of the land is wooded; to the east and north lie mountains, to the west the sea. The campus has grown steadily since it opened in 1964 and now has a faculty of over 750, an undergraduate enrollment of about 8,800, and a graduate enrollment of about 2,000.

Excellence in research has been a goal of this institution since its opening fewer than twenty years ago, and an atmosphere of intellectual stimulation pervades the campus. Chemical engineering is housed in Urey Hall, named after Harold Urey, the Nobel laureate in chemistry who helped to create one of the outstanding chemistry departments in the nation in San Diego. The adjacent physics building, Mayer Hall, takes its name from two of the founding builders of the Department of Physics here, Maria (a Nobel laureate) and Joseph Mayer. The biological sciences are a special strength here, with strong interaction with the School of Medicine (on campus) and the Salk Institute (literally across the street). Several Nobel laureates in the biological sciences are on this campus, including Dr. Jonas Salk, and Francis Crick.

The chancellor is the chief academic officer of this campus, and sets the tone and standard of excellence that characterizes academic pursuits at UCSD. The most recent former chancellor, who recently returned to his research in biochemistry, is Dr. William McElroy, who prior to becoming chancellor in 1972, was head of the National Science Foundation. His successor as chancellor, since 1980, is Dr. Richard Atkinson, a distinguished psychologist, and himself head of the National Science Foundation prior to his appointment at UCSD.

Chemical Engineering

The administrative structure on this campus is nontraditional. Chemical engineering exists not as a department, but as a formal program within a large broad-based engineering department.

The Department of Applied Mechanics and Engineering Sciences (AMES) houses a faculty of thirty who have created a set of distinct but interacting programs of study in a variety of fields.

The Department of AMES offers graduate instruction leading to the M.S. and Ph.D. degrees in the fields of applied mechanics, bioengineering, chemical engineering, engineering physics, systems science, and applied ocean science.

The instructional and research programs are characterized by strong interdisciplinary relationships with the Departments of Mathematics, Physics, and Chemistry, with Scripps Institution of Oceanography, and with associated campus institutes such as the Energy Center.

Graduate students may work toward an advanced degree in chemical engineering under the direction of those faculty appointed formally in chemical engineering, or under the direction of other AMES faculty whose interests include areas of study traditionally found in chemical engineering departments.

The Faculty and Their Research Interests

Chau, Pao C.

Assistant Professor of Chemical Engineering: homogeneous and heterogeneous catalysis, membrane science, transport phenomena, and biochemical engineering.

Gibson, Carl H.

Professor of Chemical Engineering and Oceanography: theoretical and experimental studies of turbulence and turbulent mixing.

Gough, David A.

Associate Professor of Bioengineering: electrochemical monitoring of biological materials, synthetic membranes, material properties, enzyme kinetics.

Libby, Paul A.

Professor of Fluid Mechanics: turbulent flows including: theoretical and experimental studies of variable density turbulence; turbulent flows involving chemical reactions; and heat transfer.

Middleman, Stanley

Professor of Chemical Engineering: fluid dynamics, polymer rheology, biochemical engineering (membranes and enzymes).

Miller, David R.

Professor of Chemical Engineering: gas phase chemical kinetics and gas-surface interactions, heterogeneous catalysis.

Olfe, Daniel B.

Professor of Engineering Physics: theoretical fluid dynamics and heat transfer: capillary instability.

Penner, Stanford S.

Professor of Engineering Physics and Director of the UCSD Energy Center: high-temperature gas dynamics, radiative heat transfer; combustion.

Schmid-Schoenbein, Geert W.

Assistant Professor of Bioengineering: microcirculatory research: rheological properties of tissue and blood, mass transport; mechanics of leukocyte migration.

Sebald, Anthony V.

Associate Professor of Engineering Science: macro energy and economic policy analysis, environmental effects of energy systems, solar based energy supply systems.

Seshadri, K.

Assistant Professor of Chemical Engineering: combustion, high temperature transport phenomena.

For More Information Write To:

Chemical Engineering
AMES B-010, UCSD
La Jolla, CA 92093

UNIVERSITY OF CALIFORNIA

SANTA BARBARA



FACULTY AND RESEARCH INTERESTS

SANJOY BANERJEE

Ph.D. (Waterloo)
(Vice Chairman, Nuclear Engineering)
Two Phase Flow, Reactor Safety,
Nuclear Fuel Cycle Analysis
and Wastes

H. CHIA CHANG Ph.D. (Princeton)
Chemical Reactor Modeling,
Applied Mathematics

HENRI FENECH Ph.D. (M.I.T.)
Nuclear Systems Design and Safety,
Nuclear Fuel Cycles, Two-Phase Flow,
Heat Transfer.

OWEN T. HANNA Ph.D. (Purdue)
(Chairman)
Theoretical Methods, Chemical
Reactor Analysis, Transport
Phenomena.

GLENN E. LUCAS Ph.D. (M.I.T.)
Radiation Damage, Mechanics of
Materials.

DUNCAN A. MELLICHAMP
Ph.D. (Purdue)
Computer Control, Process
Dynamics, Real-Time Computing.

JOHN E. MYERS

Ph.D. (Michigan)
(Dean of Engineering)
Boiling Heat Transfer.

G. ROBERT ODETTE

Ph.D. (M.I.T.)
Radiation Effects in Solids, Energy
Related Materials Development.

A. EDWARD PROFIO

Ph.D. (M.I.T.)
Bionuclear Engineering, Fusion
Reactors, Radiation Transport
Analyses.

ROBERT G. RINKER

Ph.D. (Caltech)
Chemical Reactor Design, Catalysis,
Energy Conversion, Air Pollution.

ORVILLE C. SANDALL

Ph.D. (Berkeley)
Transport Phenomena, Separation
Processes.

DALE E. SEBORG

Ph.D. (Princeton)
Process Control, Computer Control,
Process Identification.

PROGRAMS AND FINANCIAL SUPPORT

The Department offers M.S. and Ph.D. degree programs. Financial aid, including fellowships, teaching assistantships, and research assistantships, is available. Some awards provide limited moving expenses.

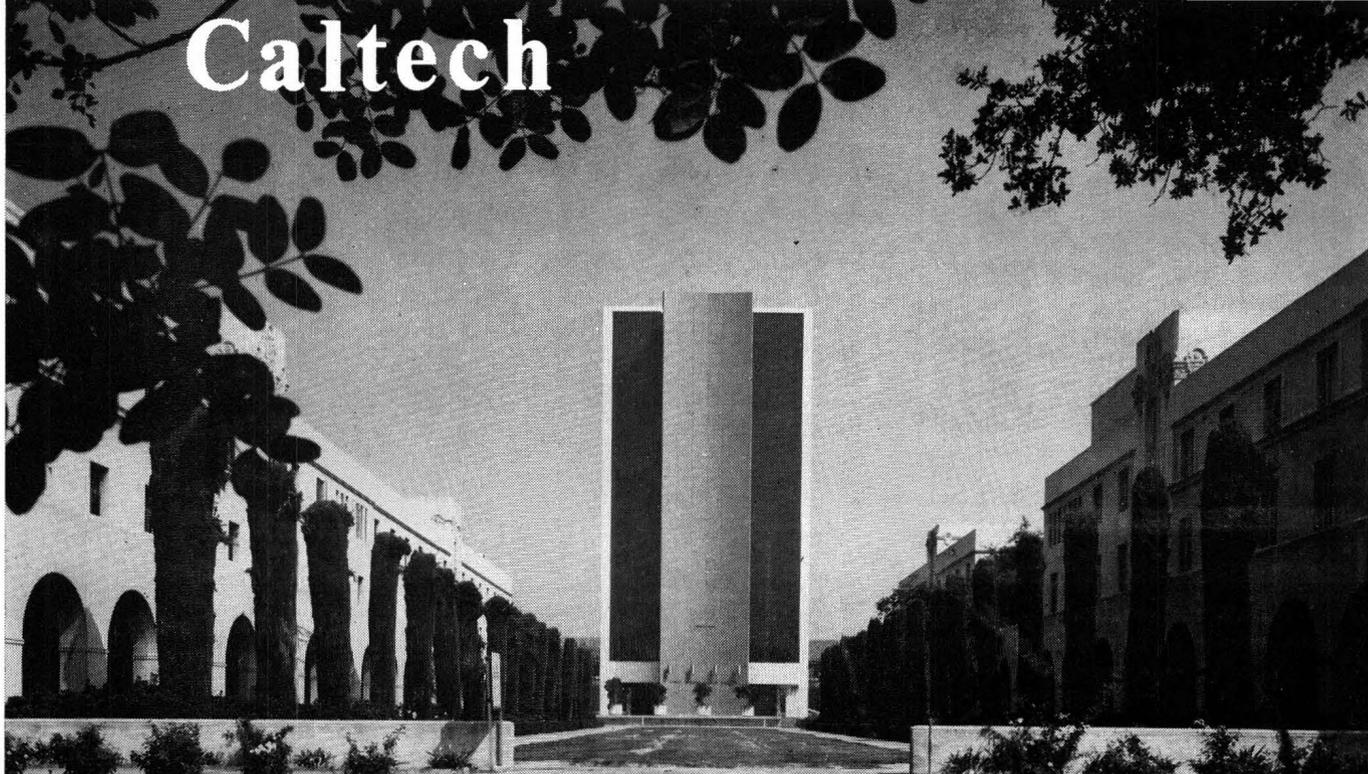
THE UNIVERSITY

One of the world's few seashore campuses, UCSB is located on the Pacific Coast 100 miles northwest of Los Angeles and 330 miles south of San Francisco. The student enrollment is over 14,000. The metropolitan Santa Barbara area has over 150,000 residents and is famous for its mild, even climate.

For additional information and applications, write to:

Professor Owen T. Hanna, Chairman
Department of Chemical & Nuclear
Engineering
University of California,
Santa Barbara, CA 93106

Caltech



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

A course of study is selected in consultation with one or more of the faculty listed below. Required courses are minimal. The Master of Science degree is normally completed in one calendar year and a thesis is not required. A special M.S. option, involving either research or an integrated design project, is a feature to the overall program of graduate study. The Ph.D. degree requires a minimum of three years subsequent to the B.S. degree, consisting of thesis research and further advanced study.

FINANCIAL ASSISTANCE Graduate students are supported by fellowship, research assistantship, or teaching assistantship appointments during both the academic year and the summer months. A student may carry a full load of graduate study and research in addition to any assigned assistantship duties. The Institute gives consideration for admission and financial assistance to all qualified applicants regardless of race, religion, or sex.

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

Professor L. G. Leal
Chemical Engineering
California Institute of Technology
Pasadena, California 91125

It is advisable to submit applications before February 15, 1984.

JAMES E. BAILEY, Professor
Ph.D. (1969), Rice University
Biochemical engineering; chemical reaction engineering.

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

ERIC HERBOLZHEIMER, Assistant Professor
Ph.D. (1979), Stanford University
Fluid mechanics and transport phenomena

L. GARY LEAL, Professor
Ph.D. (1969), Stanford University
Theoretical and experimental fluid mechanics; heat and mass transfer; suspension rheology; mechanics of non-Newtonian fluids.

MANFRED MORARI, Professor
Ph.D. (1977), University of Minnesota
Process control; process design

W. HENRY WEINBERG, Chevron Professor
Ph.D. (1970), University of California, Berkeley
Surface chemistry and catalysis.

C. DWIGHT PRATER, Visiting Associate
Ph.D. (1951), University of Pennsylvania
Catalysis; chemical reaction engineering; process design and development.

JOHN H. SEINFELD, Louis E. Nohl Professor,
Executive Officer
Ph.D. (1967), Princeton University
Air pollution; control and estimation theory.

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

GREGORY N. STEPHANOPOULOS, Assistant Professor
Ph.D. (1978), University of Minnesota
Biochemical engineering; chemical reaction engineering.

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

THE ULTIMATE ENTERPRISE



CARNEGIE- MELLON UNIVERSITY

for more information
write to:

**Director of Graduate Admissions
Chemical Engineering
Carnegie-Mellon University
Pittsburgh, PA 15213**

FACULTY:

JOHN L. ANDERSON
*Professor and Head of Chemical Engineering
Ph.D. University of Illinois
Research in membranes, transport of
macromolecules and colloids, surface and
electrokinetic phenomena, hindered
diffusion effects in catalysis.*

LORENZ T. BIEGLER
*Ph.D. University of Wisconsin-Madison
Assistant Professor of Chemical Engineering
Research in optimization methods for process
design, simulation and control; application to
chemical processes.*

ETHEL Z. CASASSA
*Associate Professor of Chemical Engineering
and Director of Colloids, Polymers, and Surface
Program
Ph.D. Columbia University
Research in micellization, solubilization and
adsorption phenomena; physical chemistry
of polymers and interfacial synthesis of
polyesters; aqueous coal slurries.*

MICHAEL DOMACH
*Assistant Professor of Chemical Engineering
Ph.D. Cornell University
Research in biomedical area includes
molecular biology, fermentation engineering,
enzyme engineering, computer simulation of
metabolism.*

IGNACIO E. GROSSMANN
*Associate Professor of Chemical Engineering
Ph.D. Imperial College, University of London
Research in optimal design of flexible chemical
plants; synthesis of integrated flowsheets;
mixed-integer programming.*

RAKESH K. JAIN
*Professor of Chemical Engineering
Ph.D. University of Delaware
Research in microcirculatory physiology,
transport and growth in normal and
cancerous tissues, pharmacokinetics, thin
liquid films with application in biological
and industrial systems.*

MYUNG S. JHON
*Assistant Professor of Chemical Engineering
Ph.D. University of Chicago
Research in kinetic theory of fluids, chemical
reactions, and polymer rheology, interfacial
dynamics and turbulence.*

EDMOND I. KO
*Assistant Professor of Chemical Engineering
Ph.D. Stanford University
Research in preparation and characterization
of heterogeneous catalysts, adsorption and
reaction on solid surfaces, and synthesis of
support materials.*

KUN LI
*Professor of Chemical Engineering
D.Sc. Carnegie-Mellon University
Research in heterogeneous reaction kinetics
in hot gas desulfurization, dry scrubbing,
iron ore reduction, and chalcopyrite
chlorination.*

GREGORY J. McRAE
*Assistant Professor of Chemical Engineering
and Engineering and Public Policy
Ph.D. California Institute of Technology
Research in mathematical modeling of multi
media systems, sensitivity analysis and
environmental management.*

GEOFFREY D. PARFITT
*Professor of Chemical Engineering
D.Sc. University of Bristol
Research in colloid and interface science and
technology of organic coatings; stability of
coal/water slurries; powder technology.*

GARY J. POWERS
*Professor of Chemical Engineering
Ph.D. University of Wisconsin
Research in process synthesis; safety and
reliability analysis; reaction path synthesis.*

DENNIS C. PRIEVE
*Professor of Chemical Engineering
Ph.D. University of Delaware
Research in mass transfer and fluid
mechanics applied to aqueous colloidal
systems, especially electrokinetic phenomena
and chemically driven particle motion.*

ROBERT R. ROTHFUS
*Professor of Chemical Engineering
D.Sc. Carnegie-Mellon University
Research in fluid mechanics, heat transfer
and mass transfer, process dynamics and
control, and fine-particle technology.*

PAUL J. SIDES
*Assistant Professor of Chemical Engineering
Ph.D. University of California-Berkeley
Research in electrochemical engineering;
electrolytic gas evolution; molten salt
electrometallurgy.*

HERBERT L. TOOR
*Mobay Professor of Chemical Engineering
Ph.D. Northwestern University
Research in mass and heat transfer, reactive
mixing, synfuels, and combustion.*

ARTHUR W. WESTERBERG
*Swearingen Professor of Chemical Engineering
Ph.D. Imperial College, University of London
Research in computer-aided design of
chemical processes; process flowsheeting,
optimization, dynamics, synthesis of
energy efficient processes; use of "expert
systems" in process design.*

The
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M.S. and Ph.D. Degrees**



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Robert Delcamp
Joel Fried
Rakesh Govind
David Greenberg
Daniel Hershey
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Yuen-Koh Kao
Soon-Jai Khang
Robert Lemlich
William Licht
Joel Weisman

CHEMICAL REACTION ENGINEERING AND HETEROGENEOUS CATALYSIS

Modeling and design of chemical reactors. Deactivating catalysts. Flow pattern and mixing in chemical equipment. Laser induced effects.

PROCESS SYNTHESIS

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POLYMERS

*Viscoelastic properties of concentrated polymer solutions.
Thermodynamics, thermal analysis
and morphology of polymer blends.*

AIR POLLUTION

Modeling and design of gas cleaning devices and systems.

TWO-PHASE FLOW

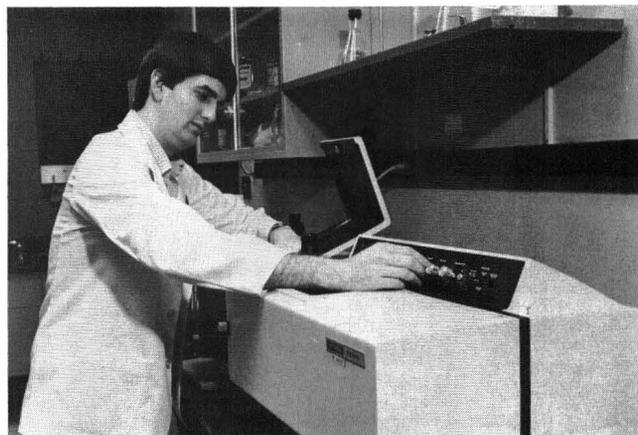
Boiling. Stability and transport properties of foam.

**THERMODYNAMIC ANALYSIS OF
LIVING HUMAN AND
CORPORATE SYSTEMS**

*Longevity, basal metabolic rate,
and Prigogine's and Shannon's
entropy formulae.*

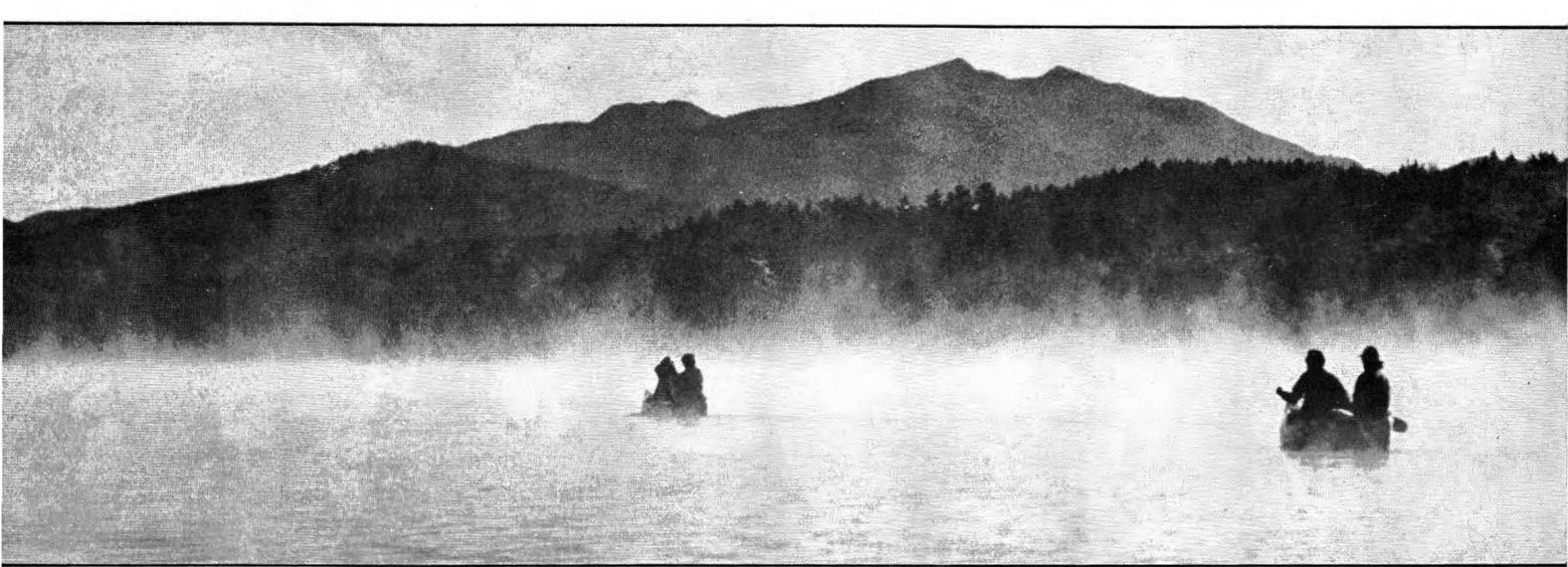
MEMBRANE SEPARATIONS

Membrane gas separation, continuous membrane reactor column, equilibrium shift, pervaporation, dynamic simulation of membrane separators, membrane preparation and characterization.



FOR ADMISSION INFORMATION

Chairman, Graduate Studies Committee
Chemical & Nuclear Engineering, #171
University of Cincinnati
Cincinnati, OH 45221



Clarkson

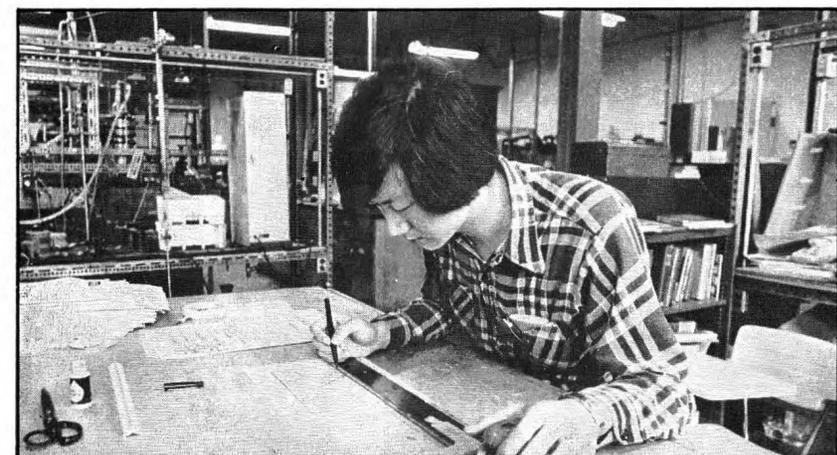
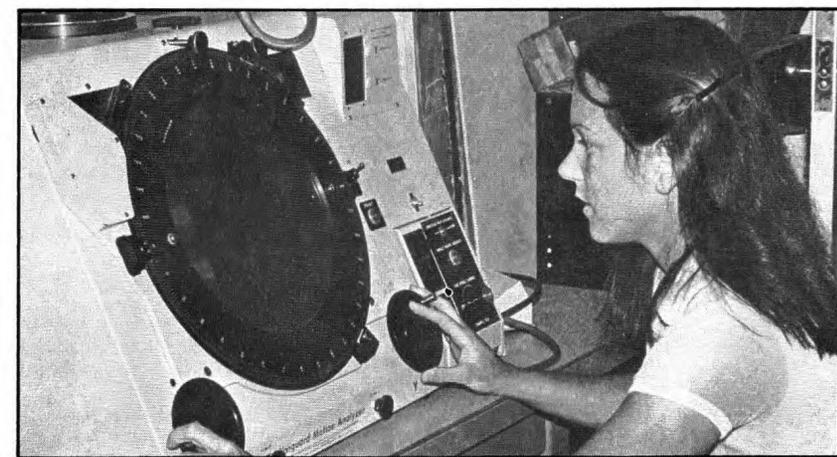
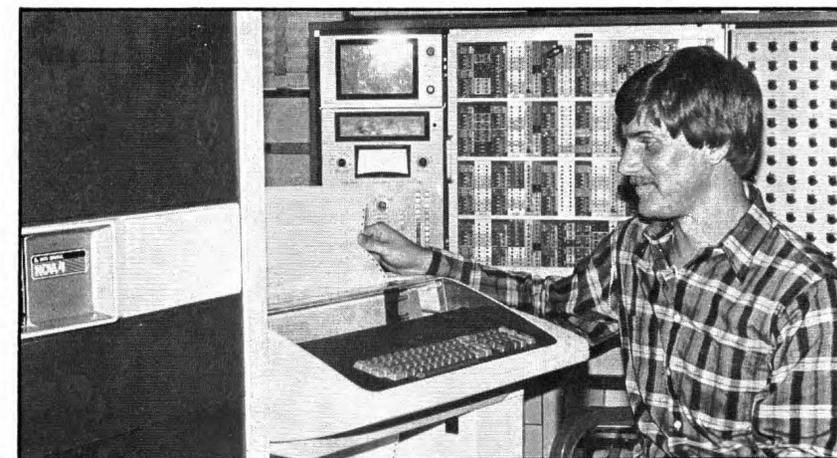
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- J. H. Gary**, Professor; Ph.D., University of Florida. Upgrading of shale oil and coal liquids, petroleum refinery processing operations, heavy oil processing.
- A. J. Kidnay**, Professor and Head; D.Sc., Colorado School of Mines. Thermodynamic properties of coal-derived liquids, vapor-liquid equilibria in natural gas systems, cryogenic engineering.
- E. D. Sloan, Jr.**, Professor; Ph.D., Clemson University. Phase equilibrium thermodynamics measurements of natural gas fluids and natural gas hydrates, thermal conductivity measurements for coal derived fluids, adsorption equilibria measurements, stagewise processes, education methods research.
- V. F. Yesavage**, Professor; Ph.D., University of Michigan. Thermodynamic properties of fluids, especially relating to synthetic fuels. Oil shale and shale oil processing; numerical methods.
- R. M. Baldwin**, Associate Professor, Ph.D., Colorado School of Mines. Coal liquefaction by direct hydrogenation, mechanisms of coal liquefaction, kinetics of coal hydrogenation, relation of coal geochemistry to liquefaction kinetics, upgrading of coal-derived asphaltenes.
- M. S. Graboski**, Associate Professor; Ph.D., Pennsylvania State University. Coal and biomass gasification processes, gasification kinetics, thermal conductivity of coal liquids, kinetics of SNG upgrading.
- M. C. Jones**, Associate Professor; Ph.D., University of California at Berkeley. Heat transfer and fluid mechanics in oil shale retorting, radiative heat transfer in porous media, free convection in porous media.
- M. S. Selim**, Associate Professor; Ph.D., Iowa State University. Flow of concentrated fine particulate suspensions in complex geometries; Sedimentation of multisized, mixed density particle suspensions.
- A. L. Bunge**, Assistant Professor; Ph.D., University of California at Berkeley. Chromatographic processes, enhanced oil recovery, minerals leaching, liquid membrane separations, ion exchange equilibria.

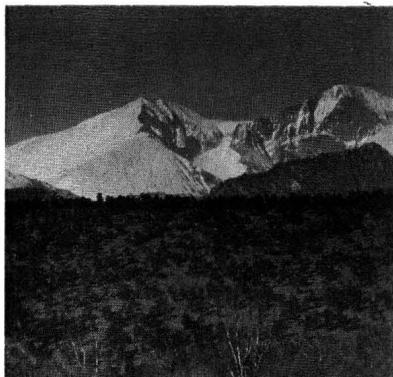
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Golden, CO 80401

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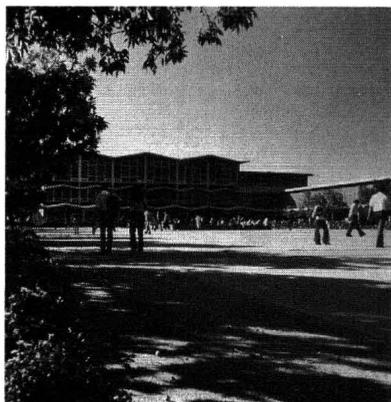
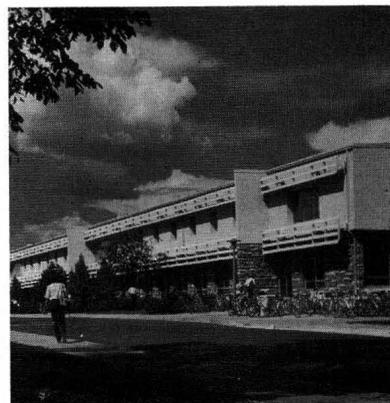


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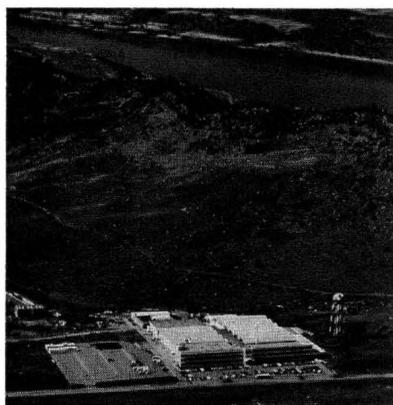
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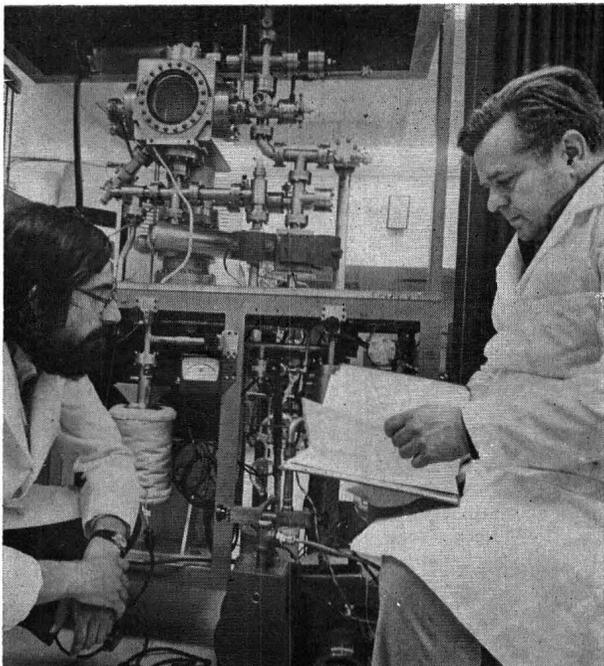
Research Areas:

Alternate Energy Sources
Biochemical Engineering
Catalysis
Computer Simulation and Control
Fermentation
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Polymeric Materials
Porous Media Phenomena
Rheology
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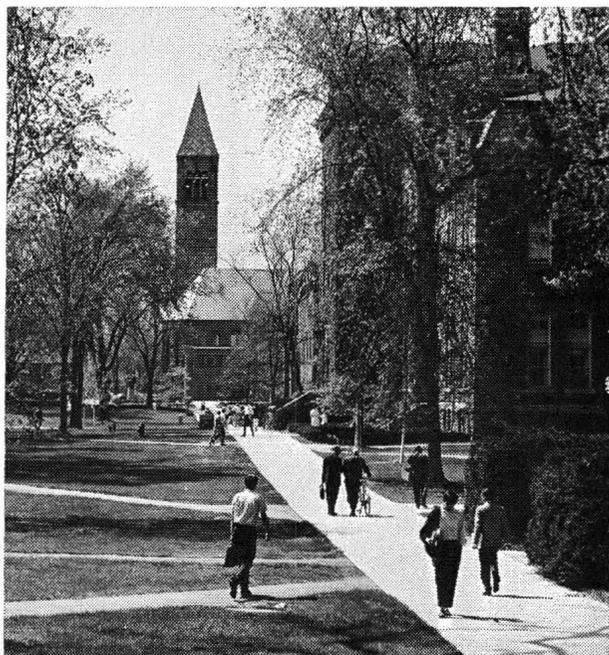
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G. C. A. Schuit (1/2 time)
J. M. Schultz
A. B. Stiles (1/2 time)
M. A. Streicher (1/2 time)
R. S. Weber

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Materials Science and Metallurgy
Fluid Mechanics, Heat and Mass Transfer
Economics and Management in the Chemical Process Industries
Chemical Reaction Engineering, Kinetics and Simulation
Catalytic Science and Technology
Biomedical Engineering—Pharmacokinetics and Toxicology
Biochemical Engineering—Fermentation and Computer Control

FOR MORE INFORMATION AND ADMISSIONS MATERIALS, WRITE:
Graduate Advisor
Department of Chemical Engineering
University of Delaware
Newark, Delaware 19711

Chemical Engineering

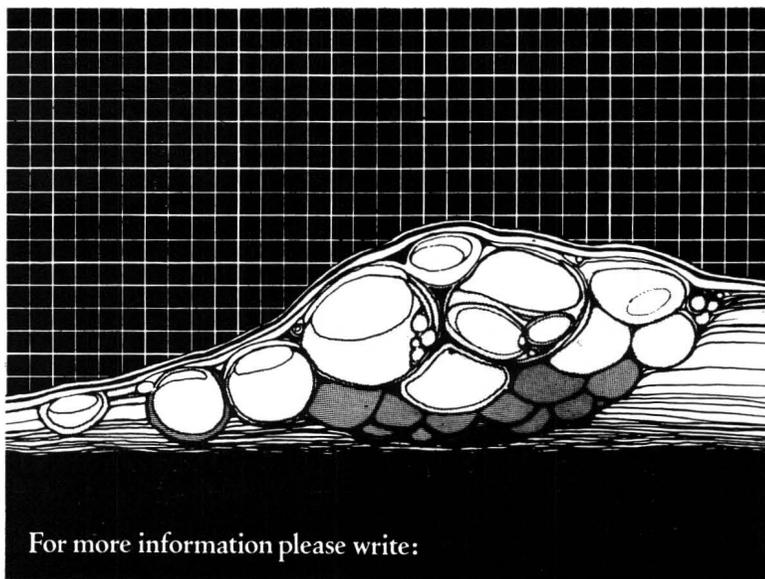
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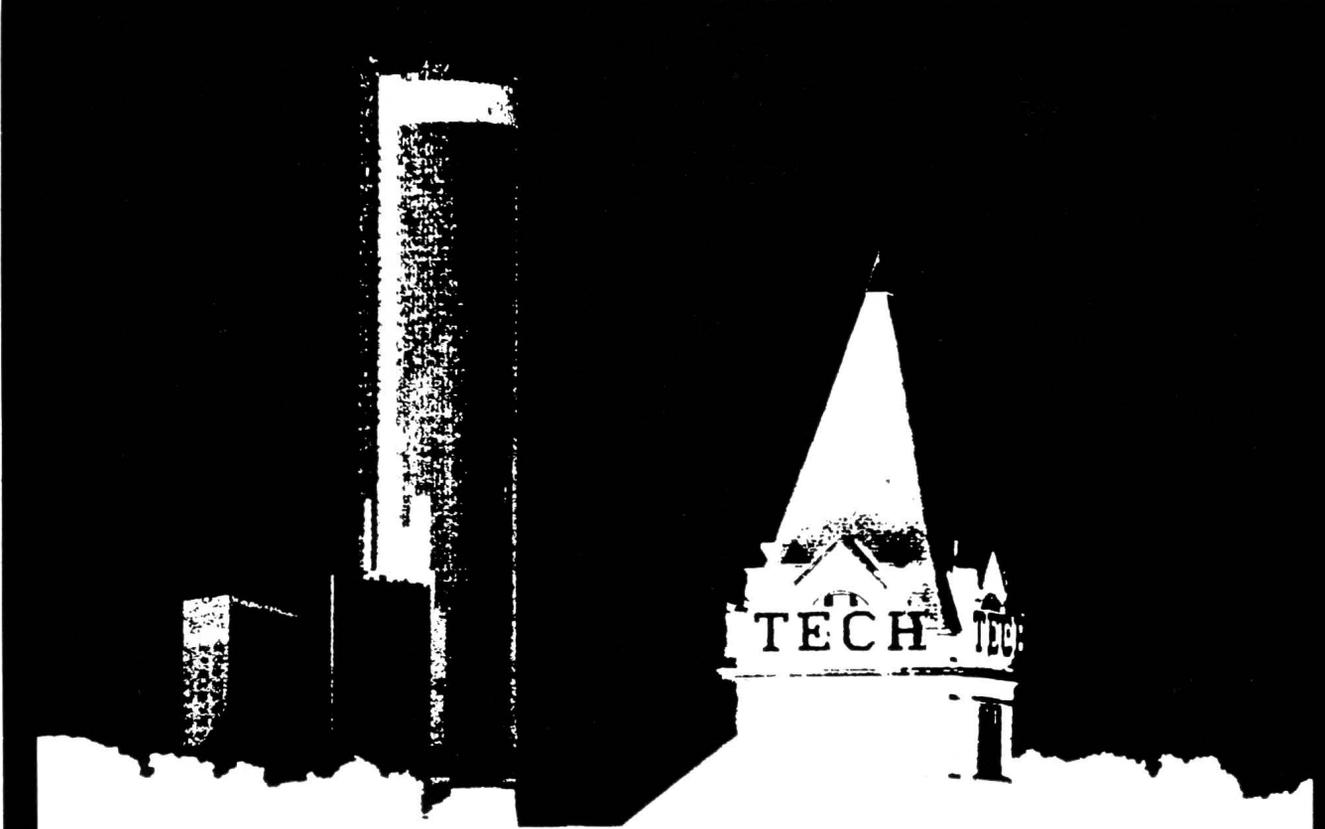
F A C U L T Y

Tim Anderson Thermodynamics, Semiconductor Processing/ **Seymour S. Block** Biotechnology
Ray W. Fahien Transport Phenomena, Reactor Design/ **Gar Hoflund** Catalysis, Surface Science
Lew Johns Applied Mathematics/ **Dale Kirmse** Process Control, Computer Aided Design, Biotechnology/ **Hong H. Lee** Reactor Design, Catalysis/ **Gerasimos K. Lyberatos** Optimization, Biochemical Processes/ **Frank May** Separations
Ranga Narayanan Transport Phenomena/ **John O'Connell** Statistical Mechanics, Thermodynamics
Dinesh O. Shah Enhanced Oil Recovery, Biomedical Engineering/ **Spyros Svoronos** Process Control/ **Robert D. Walker** Surface Chemistry, Enhanced Oil Recovery/ **Gerald Westermann-Clark** Electrochemistry, Transport Phenomena



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Department of Chemical Engineering
University of Florida
Gainesville, Florida 32611



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Process Synthesis and
Optimization
Pulp and Paper Engineering
Reactor Design
Thermodynamics
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For more information write:

**Dr. Gary W. Poehlein
School of Chemical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332**

Graduate Programs in Chemical Engineering

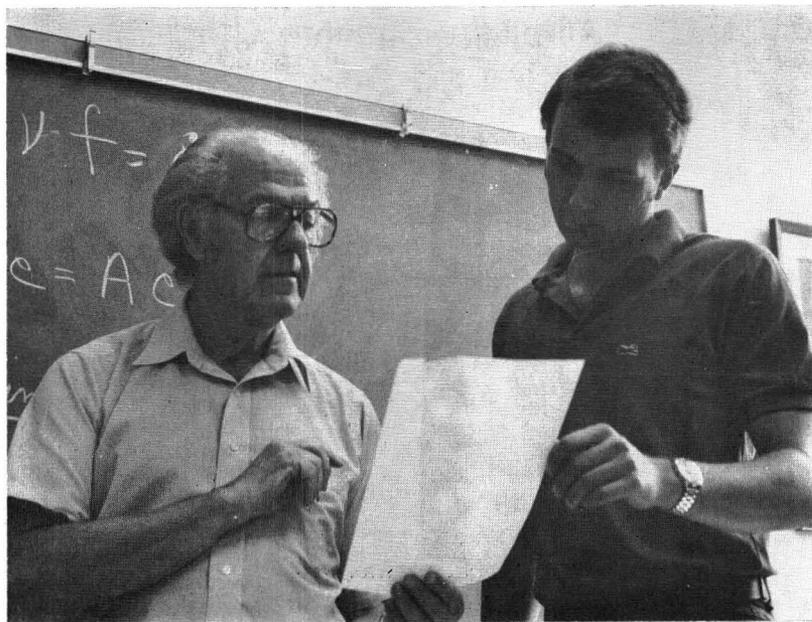
University of Houston

The Department of Chemical Engineering at the University of Houston has developed seven areas of special research strength:

- Chemical Reaction Engineering Catalysis
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- Solid-liquid Separation
- Air Pollution Modeling
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Director, Graduate Admissions
Department of Chemical Engineering
University of Houston
Houston, Texas 77004
(Phone 713/749-4407)



The faculty:

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O. A. Asbjornsen
V. Balakotaiah
E. L. Claridge
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H. A. Deans
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FACULTY AND RESEARCH ACTIVITIES

Francisco J. Brana-Mulero
Ph.D., University of Wisconsin, 1980
Assistant Professor

Process synthesis, operations research, optimal process control, optimization of large systems, numerical analysis, theory of nonlinear equations.

T. S. Jiang
Ph.D., Northwestern University, 1981
Assistant Professor

Interfacial Phenomena, multiphase flows, flow through porous media, suspension rheology

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

Kinetics of gas reactions, energy transfer processes, laser diagnostics

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

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

Sohail Murad
Ph.D., Cornell University, 1979
Assistant Professor

Thermodynamics and transport properties of fluids, computer simulation and statistical mechanics of liquids and liquid mixtures

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

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

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

Catalysis, chemical reaction engineering, energy transmission, modeling and optimization

Raffi M. Turian
Ph.D., University of Wisconsin, 1964
Professor

Slurry transport, suspension and complex fluid flow and heat transfer, porous media processes, mathematical analysis and approximation.

The MS program, with its optional thesis, can be completed in one year. Evening M.S. can be completed in three years.

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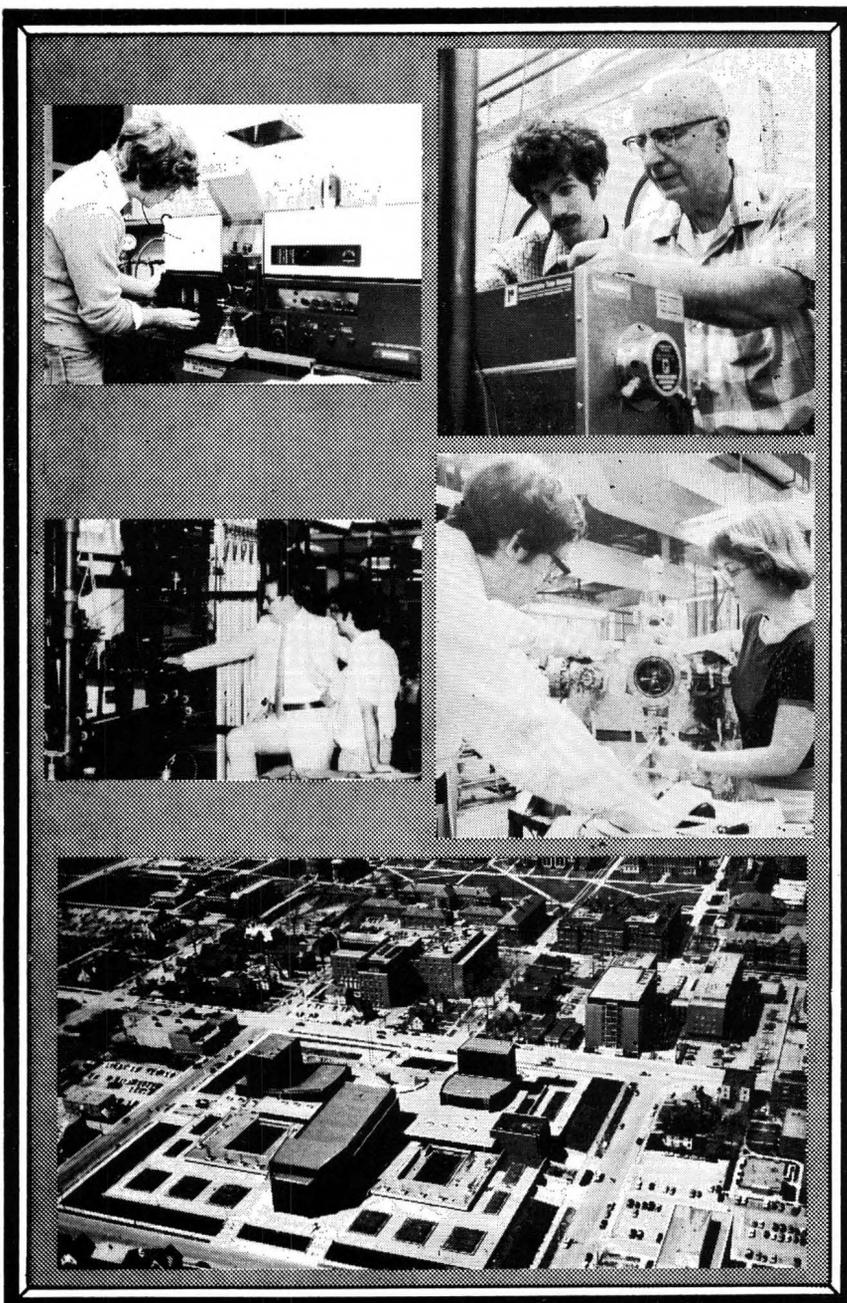
Professor S. Murad, Chairman

**The Graduate Committee
Department of Chemical Engineering
University of Illinois at Chicago
Box 4348,
Chicago, Illinois 60680**

CHEMICAL ENGINEERING AT THE

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University of Illinois at Urbana-Champaign
Department of Chemical Engineering
113 Roger Adams Laboratory
1209 W. California
Urbana, Illinois 61801-3791

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Electrochemical Engineering

Harry G. Drickamer, Professor
High Pressure Studies, Structure
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Molecular Thermodynamics,
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Fluid Dynamics, Convective Heat
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Jonathan J. L. Higdon,
Assistant Professor
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Assistant Professor
Catalysis, Surface Science

Walter G. May
Visiting Professor
Chemical Process Engineering

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Polymer Crystallization, Transport
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Joseph A. Shaeiwitz,
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Mass Transfer, Interfacial and
Colloidal Phenomena

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Associate Professor
Process Flowsheeting
and Optimization

James W. Westwater, Professor
Boiling Heat Transfer, Phase
Changes

Graduate Studies in Chemical Engineering

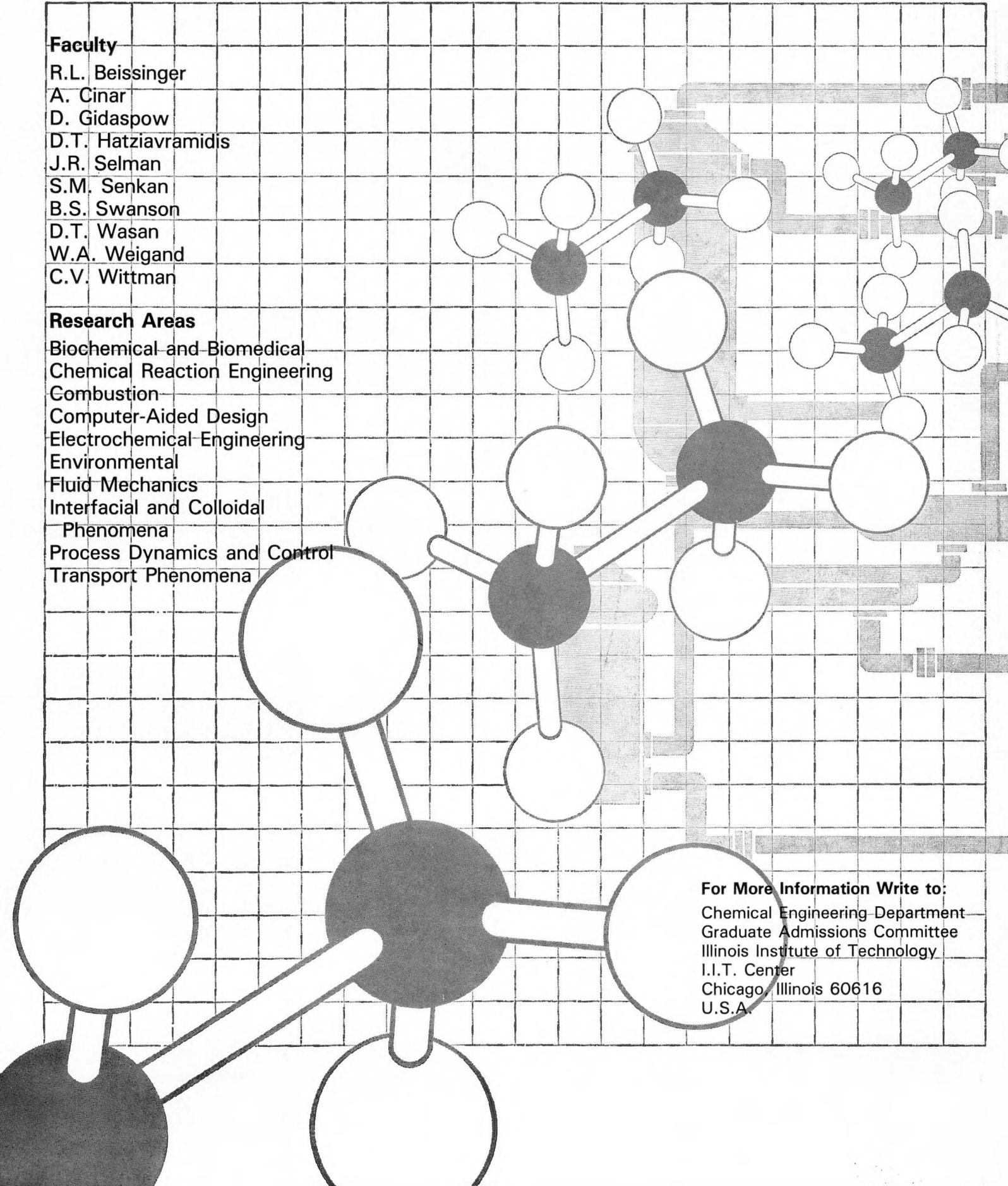
Illinois Institute of Technology
Chicago, Illinois

Faculty

R.L. Beissinger
A. Cinar
D. Gidaspow
D.T. Hatzivramidis
J.R. Selman
S.M. Senkan
B.S. Swanson
D.T. Wasan
W.A. Weigand
C.V. Wittman

Research Areas

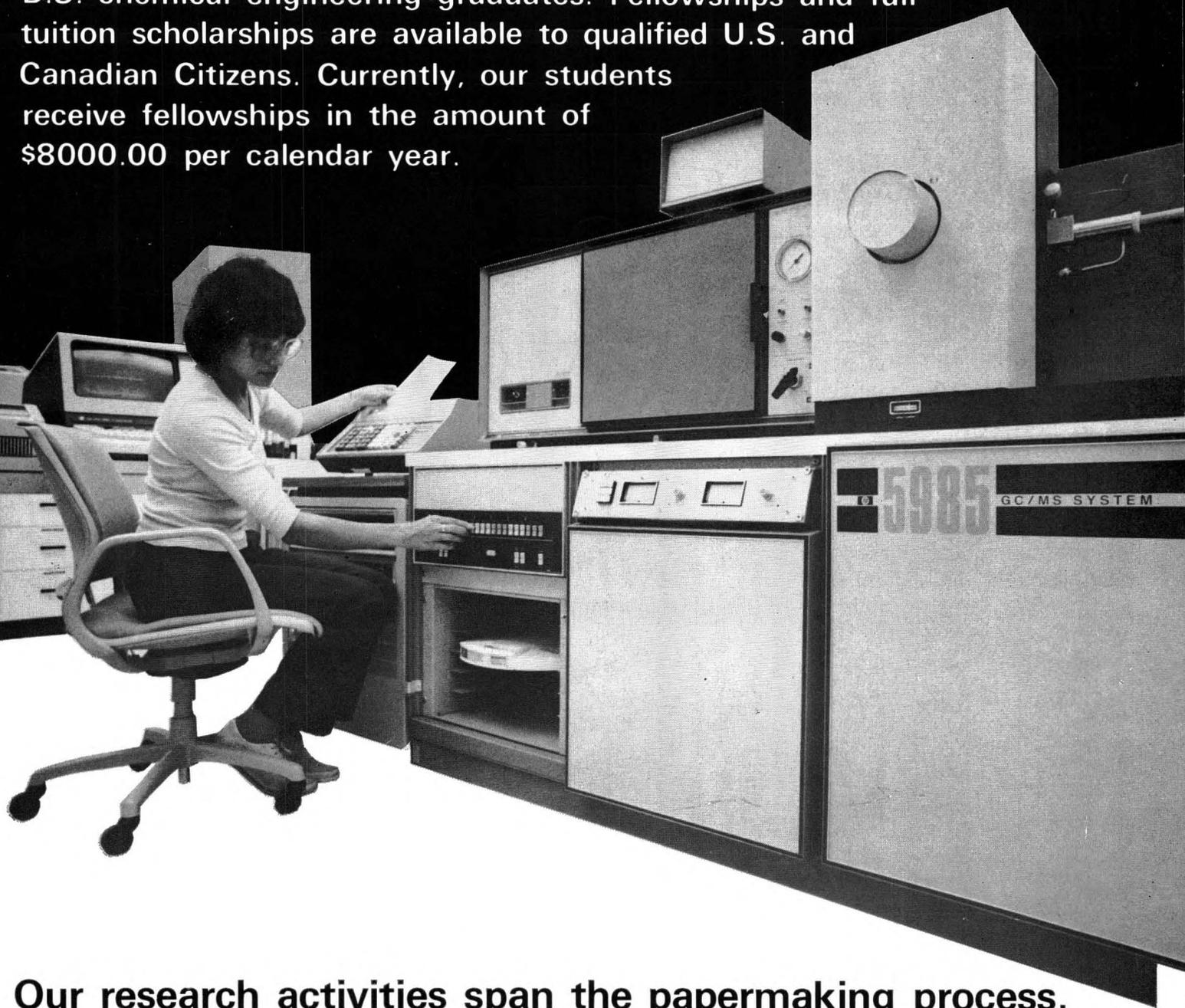
Biochemical and Biomedical
Chemical Reaction Engineering
Combustion
Computer-Aided Design
Electrochemical Engineering
Environmental
Fluid Mechanics
Interfacial and Colloidal
Phenomena
Process Dynamics and Control
Transport Phenomena



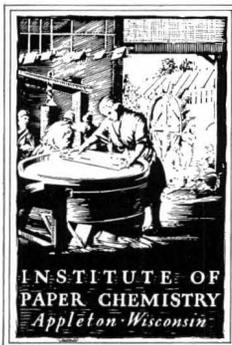
For More Information Write to:
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Illinois Institute of Technology
I.I.T. Center
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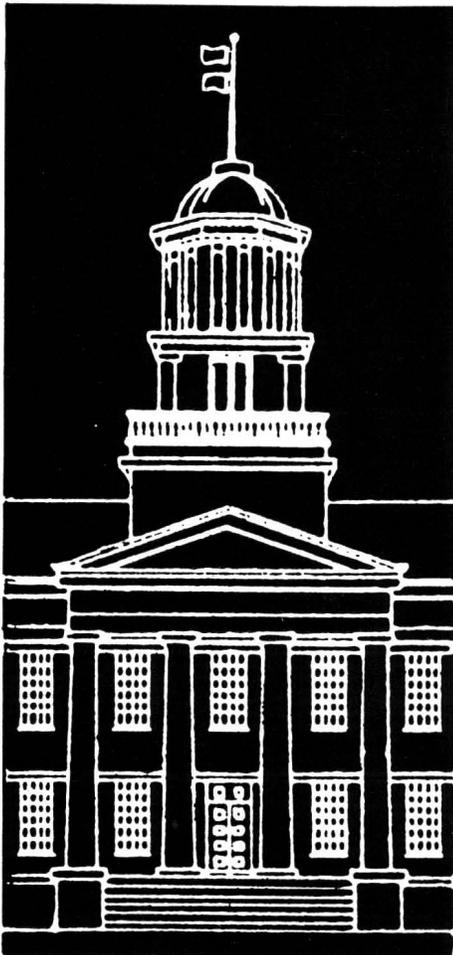
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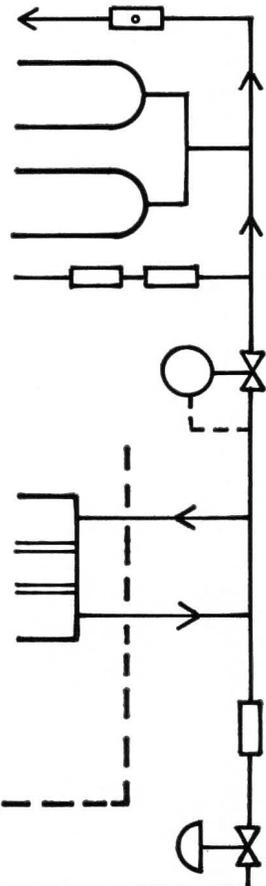
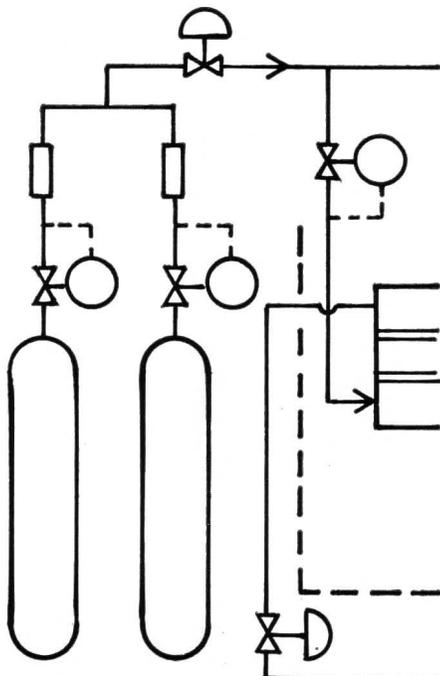
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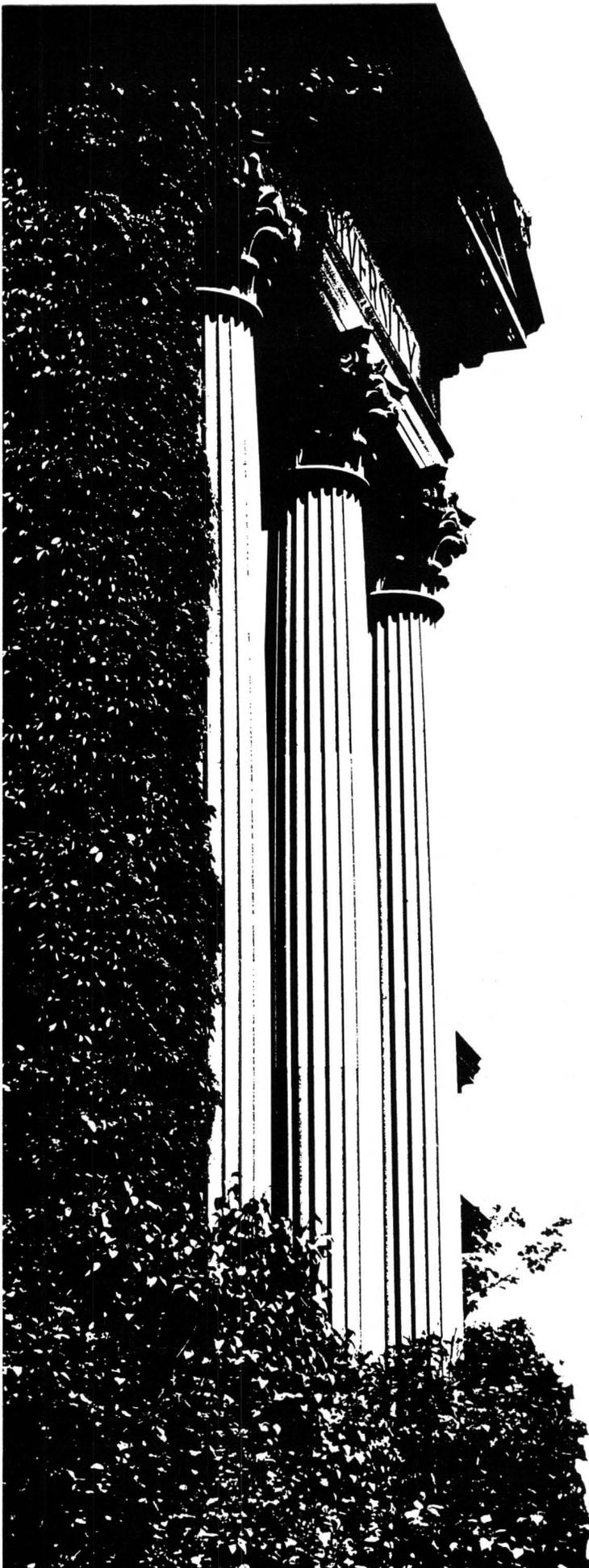
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Faculty

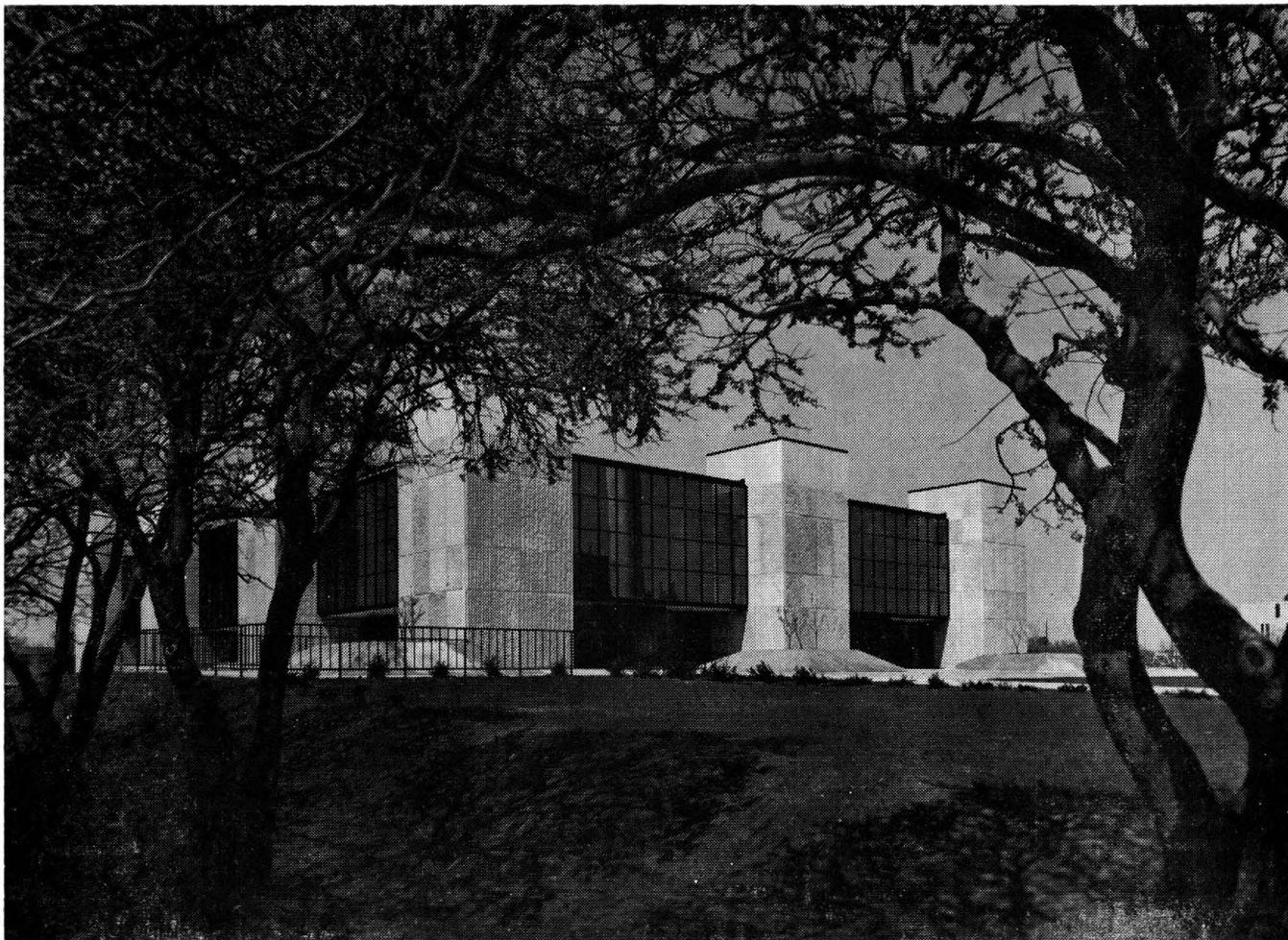
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Research Interests

Biochemical Engineering
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Catalysis and Kinetics
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Crystallization Technology
Energy Conversion
Fluid Mechanics and Rheology
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Polymer Technology
Process Instrumentation, Optimization and Control
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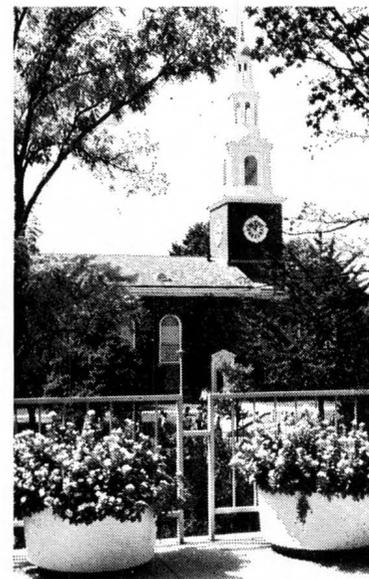
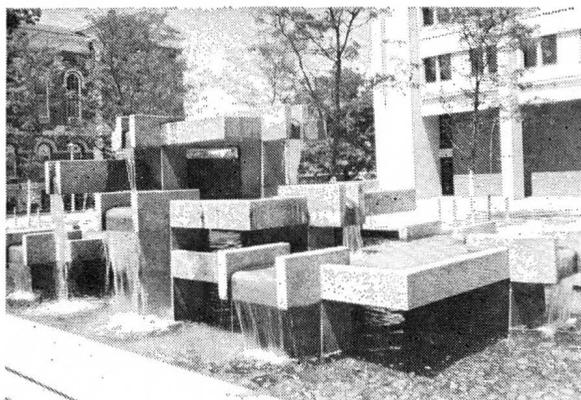
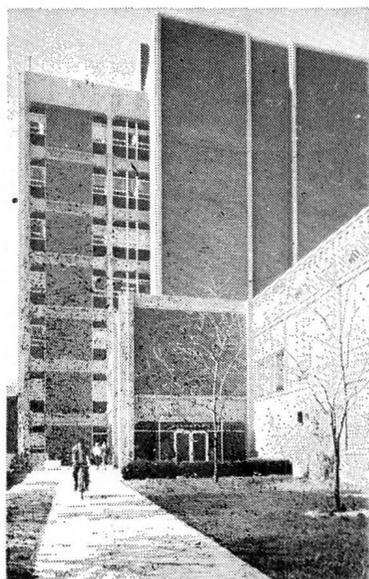
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Professor B. G. Kyle
Durland Hall
Kansas State University
Manhattan, Kansas 66506

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PROCESS DYNAMICS AND CONTROL
CHEMICAL REACTION ENGINEERING
MATERIALS SCIENCE
SOLIDS MIXING
CATALYSIS AND FUEL SYNTHESIS
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THE FACULTY AND THEIR RESEARCH INTERESTS

J. Berman, Ph.D., Northwestern
Biomedical Engineering; Cardiovascular
Transport Phenomena; Blood Oxygenation

D. Bhattacharyya, Ph.D.
Illinois Institute of Technology
Novel Separation Processes; Membranes;
Water Pollution Control

G. F. Crewe, Ph.D., West Virginia
Catalytic Hydrocracking of
Polyaromatics; Coal Liquefaction

C. E. Hamrin, Ph.D., Northwestern
Coal Liquefaction; Catalysis; Nonisothermal Kinetics

R. I. Kermode, Ph.D., Northwestern
Process Control and Economics

L. K. Peters, Ph.D., Pittsburgh
Atmospheric Transport; Aerosol Phenomena

E. D. Moorhead, Ph.D., Ohio State
Electrochemical Processes; Computer
Measurement Techniques and Modeling

A. K. Ray, Ph.D., Clarkson
Heat and Mass Transfer in Knudsen
Regime; Transport Phenomena

J. T. Schrodt, Ph.D., Louisville
Simultaneous Heat and Mass Transfer;
Fuel Gas Desulfurization

Fellowships and Research Assistantships are Available to Qualified Applicants

For details write to:

E. D. Moorhead
Director for Graduate Studies
Chemical Engineering Department
University of Kentucky
Lexington, Kentucky 40506-0046

GRADUATE STUDY IN

CHEMICAL ENGINEERING

LOUISIANA STATE UNIVERSITY

PROGRAMS

The Department of Chemical Engineering at LSU offers the M.S. and Ph.D. degrees through a broad program of studies that allows students to concentrate on their particular interests. Some 100 master's and doctoral candidates are presently training and studying within the department.

FACULTY AND RESEARCH

A strong faculty, with diverse research interests, provides a broad base of expertise from which thesis or dissertation topics can be chosen. Current faculty research interests include biochemical processes, catalysis, combustion, computer-aided design, optimization, pollution dynamics and control, process control and simulation, reactor design, separation science, sugar technology, thermodynamic properties, and transport phenomena. Collaborative research projects are also conducted in association with the Audubon Sugar Institute, Hazardous Waste Research Center, Center for Energy Studies, Coastal Studies Institute, Water Resources Institute, Mining and Minerals Resources Research Institute, and other LSU organizations.

FINANCIAL AID

Financial support is usually available to high-ranking graduates of U.S. universities. The prestigious Alumni Federation Fellowships provide stipends of \$10,000 a year for four years, tax exempt, and are available to outstanding Ph.D. candidates. Full-time graduate students receiving fellowships or assistantships are also exempt from tuition and most University fees.

THE COMMUNITY

The University is located in proximity to the corridor of petrochemical industries stretching north of Baton Rouge down the Mississippi River to the fringes of New Orleans. Some 280 chemical plants and refineries within this complex enjoy technological rapport and exchange with the University and the Department of Chemical Engineering.

Baton Rouge, with a metropolitan population of about 400,000, is in the middle of Louisiana, a sportsman's paradise of hunting, fishing, and water recreation in the nearby lakes, bayous, marshes, and the Gulf of Mexico.

For further information, write
Director of Graduate Instruction
Department of Chemical Engineering
Louisiana State University
Baton Rouge, LA 70803



University of Maine at Orono

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

- Sponsored projects valued at \$1 million per year are in progress.
- Faculty is supported by extensive state-of-the-art facilities.
- Relevancy of the Department's research is insured by continuous liaison with engineers and scientists from industry who help guide the faculty concerning emerging needs and activities of other laboratories.
- Several research and teaching assistantships are available.
- Outstanding candidates (GPA greater than 3.75/4.00) wishing to pursue the Ph.D. are invited to apply for President's Fellowships which provide \$4000 per year in addition to regular stipend and free tuition.

THE FACULTY AND THEIR RESEARCH

Dr. William H. Ceckler
Sc.D., MIT, 1960
Flow through porous media
Paper manufacture
Process simulation

Dr. Albert Co
Ph.D., Wisconsin, 1979
Transport phenomena
Polymeric fluid dynamics
Rheology

Dr. Arthur L. Fricke
Ph.D., Wisconsin, 1962
Properties of polymeric systems
Polymer processing and design
Rheology of polymeric fluids

Dr. Joseph M. Genco
Ph.D., Ohio State, 1965
Process engineering
Pulp and paper technology
Wood delignification

Dr. John C. Hassler
Ph.D., Kansas State, 1966
Process analysis and

numerical methods
Instrumentation and real-time computer applications

Dr. Marqueta K. Hill
Ph.D., U of California, 1966
Black liquor chemistry
Pulping chemistry
Ultrafiltration

Dr. John J. Hwalek
Ph.D., Illinois, 1982
Process control systems
Alternative energy resources

Dr. Erdogan Kiran
Ph.D., Princeton, 1974
Polymer physics and chemistry
Pulp and paper technology
Thermal analysis and pyrolysis

Dr. Kenneth I. Mumme
Ph.D., Maine, 1970
Process modeling and control
System identification and optimization

Dr. Hemant Pendse
Ph.D., Syracuse, 1980
Porous media modeling

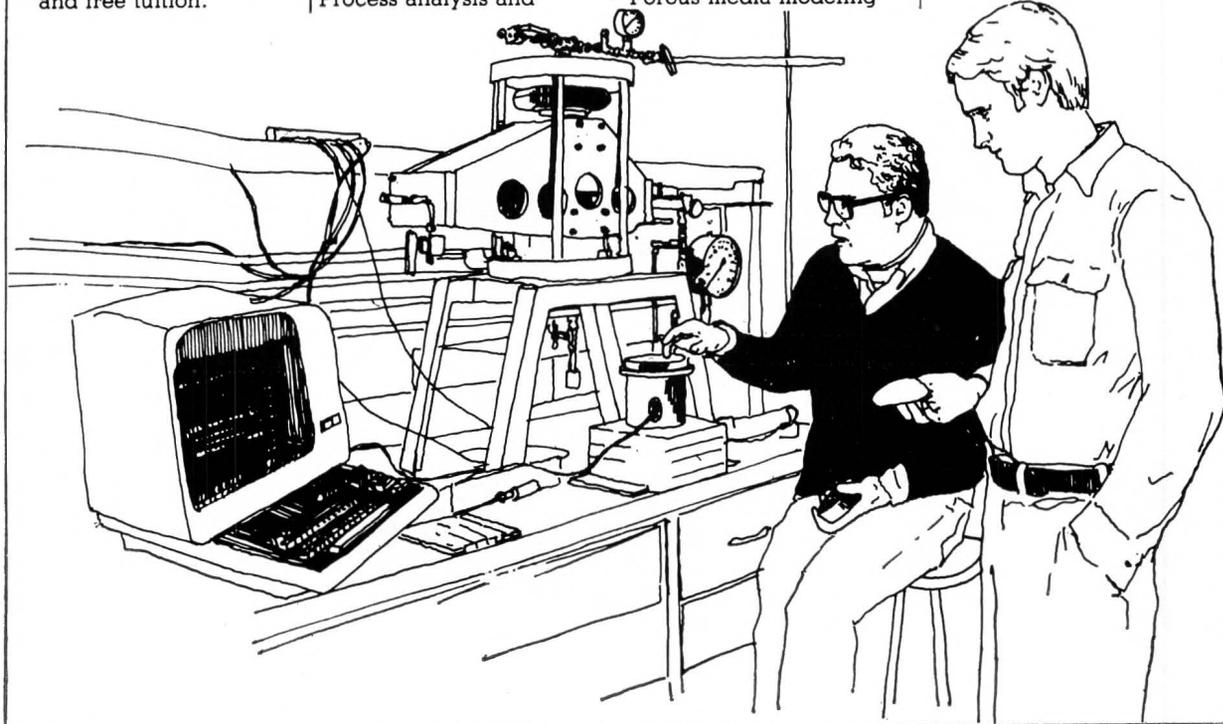
Colloidal phenomena
Particulate systems

Dr. Ivar H. Stockel
Sc.D., MIT, 1959
Pulp and paper technology
Applied mathematics
Droplet formation

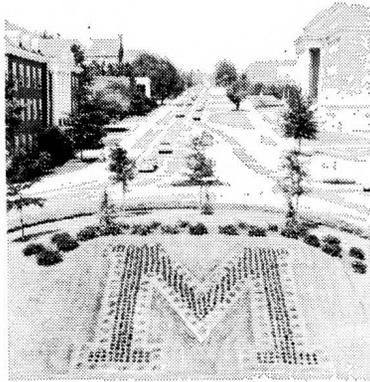
Dr. Edward V. Thompson
Ph.D., Brooklyn Polytech., 1962
Polymer material properties
Membrane separation processes
Paper manufacture

For information brochure and application materials contact:

Dr. Hemant Pendse,
Chemical Engineering
Department
University of Maine
at Orono
Orono, ME 04469
207/581-2290

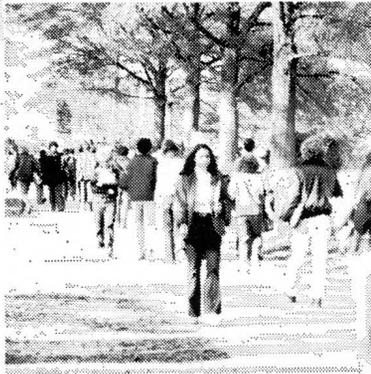


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The University of Maryland is located approximately 10 miles from the heart of the nation, Washington, D.C. Excellent public transportation permits easy access to points of interest such as the Smithsonian, National Gallery, Congress, White House, Arlington Cemetery, and the Kennedy Center. A short drive west produces some of the finest mountain scenery and recreational opportunities on the east coast. An even shorter drive east brings one to the historic Chesapeake Bay with its delicious seafood.



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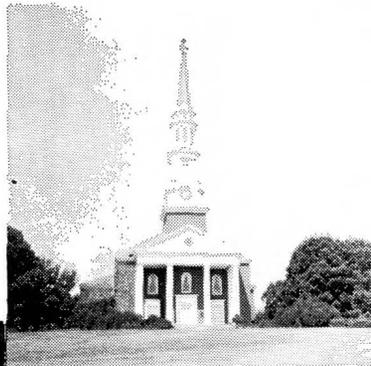
M.S. and Ph.D. programs in Chemical Engineering.

Financial Aid Available:

Teaching and Research Assistantships at \$6,800, plus tuition reimbursement are available.

Faculty:

Robert B. Beckmann
Theodore W. Cadman
Richard V. Calabrese
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Randolph T. Hatch
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Research Areas:

Aerosol Mechanics
Air Pollution Control
Biochemical Engineering
Biomedical Engineering
Fermentation
Laser Anemometry
Mass Transfer
Polymer Processing
Risk Assessment
Separation Processes
Simulation

For Applications and Further Information, Write:

Professor Thomas J. McAvoy
Department of Chemical and Nuclear Engineering
University of Maryland
College Park, Md. 21742



UNIVERSITY of MASSACHUSETTS

Amherst

The Chemical Engineering Department at the University of Massachusetts offers graduate programs leading to M.S. and Ph.D. degrees in Chemical Engineering. Active research areas include polymer engineering, catalysis, design, and basic engineering sciences. Close coordination characterizes research in polymers which can be conducted in either the Chemical Engineering Department or our prestigious Polymer Science and Engineering Department. Financial aid in the form of research assistantships and teaching assistantships is available. Course of study and area of research are selected in consultation with one or more of the faculty listed below.

● CHEMICAL ENGINEERING ●

W. C. CONNER

Catalysis, Kinetics, Surface diffusion

M. F. DOHERTY

Distillation, Thermodynamics, Design

J. M. DOUGLAS

Process design and control, Reactor engineering

J. W. ELDRIDGE

Kinetics, Catalysis, Phase equilibria

V. HAENSEL

Catalysis, Kinetics

R. S. KIRK

Kinetics, Ebullient bed reactors

J. R. KITRELL (Adjunct Professor)

Kinetics and catalysis, Catalyst deactivation

R. L. LAURENCE*

Polymerization reactors, Fluid mechanics

R. W. LENZ*

Polymer synthesis, Kinetics of polymerization

M. H. LOCKE

Computer-aided design

M. F. MALONE

Rheology, Polymer processing, Design

P. A. MONSON

Statistical mechanics of gases

K. M. NG

Enhanced oil recovery, Two-phase flows

J. M. OTTINO*

Mixing, Fluid mechanics, Polymer engineering

F. I. SHINSKEY (Adjunct Professor)

Process Control

M. VANPEE

Combustion, Spectroscopy

H. H. WINTER*

Polymer rheology and processing, Heat transfer

B. E. YDSTIE

Process Control

● POLYMER SCIENCE AND ENGINEERING ●

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Polymerization catalysts, Biopolymers, Polymer degradation

R. FARRIS

Polymer composites, Mechanical properties, Elastomers

S. L. HSU

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F. E. KARASZ

Polymer transitions, Polymer blends, Conducting polymers

W. J. MacKNIGHT

Viscoelastic and mechanical properties of polymers

T. J. McCARTHY

Polymer synthesis, Polymer surfaces

M. MUTHUKUMAR

Statistical mechanics of polymer solutions, gels, and melts

R. S. PORTER

Polymer rheology, Polymer processing

R. STEIN

Polymer crystallinity and morphology, Characterization

E. L. THOMAS*

Electron microscopy, Polymer morphology, x-Ray Scattering

**Joint appointments in Chemical Engineering and Polymer Science and Engineering*

For further details, please write to:

Prof. J. W. Eldridge
Dept. of Chemical Engineering
University of Massachusetts
Amherst, Mass. 01003
413-545-0276

Prof. E. Thomas
Dept. of Polymer Science and Engineering
University of Massachusetts
Amherst, Mass. 01003
413-545-0433

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J. Wei, Department Head	G. A. Huff, Jr.
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H. C. Hottel	J. E. Vivian
J. B. Howard	D. I. C. Wang
	G. C. Williams

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Energy Conversion
Environmental
Fluid Mechanics
Integrated Circuit Processing
Kinetics and Reaction Engineering
Polymers
Process Dynamics and Control
Surfaces and Colloids
Transport Phenomena



Photo by James Wei

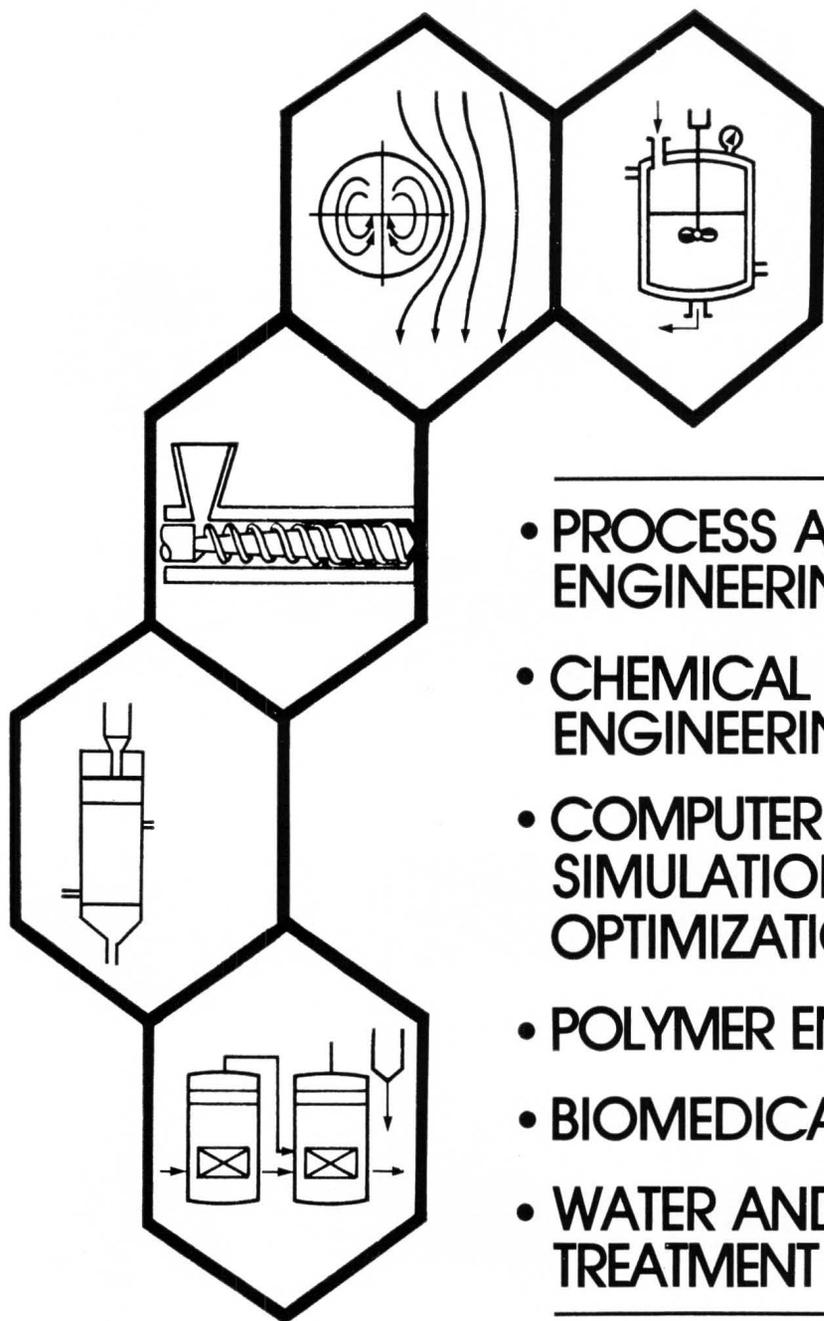
MIT also operates the School of Chemical Engineering Practice, with field stations at the General Electric Company in Albany, New York, the Bethlehem Steel Company at Bethlehem, Pennsylvania, and Brookhaven National Lab at Long Island, New York.

For Information

Chemical Engineering Headquarters
Room 66-350
MIT
Cambridge, MA 02139



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- COMPUTER CONTROL, SIMULATION AND OPTIMIZATION
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- BIOMEDICAL ENGINEERING
- WATER AND WASTEWATER TREATMENT

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PLEASE CONTACT:

**CHAIRMAN
DEPT. OF CHEMICAL ENGINEERING
McMASTER UNIVERSITY
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Brice Carnahan
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Rane Curl
MIT
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Illinois, Colorado
Erdogan Gulari
Robert, Cal Tech
Robert Kadlec
Wisconsin, Michigan
Donald Katz
Michigan
Lloyd Kempe
Minnesota
Costas Kravaris
Athens, Cal Tech
John Powers
Michigan, Berkeley
Jerome Schultz, Chairman
Columbia, Wisconsin
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Iowa State, MIT
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Cambridge, Michigan
Brymer Williams
Michigan
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Holy Cross, Cornell, Case
Edwin Young
Detroit, Michigan
Robert Ziff
Rockefeller, UCLA

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Reservoir Engineering
Heterogeneous Catalysis
Thrombogenesis
Microemulsions
Applied Numerical Methods
Dynamic Process Simulation
Ecological Simulation
Electroless Plating
Electrochemical Reactors
Polymer Physics
Polymer Processing
Composite Materials
Coal Liquefaction
Coal Gasification
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The Department of Chemical Engineering of Michigan State University has assistantships and fellowships available for students wishing to pursue advanced study. With one of these appointments it is possible for a graduate student to obtain the M.S. degree in one year and the Ph.D. in two to three additional years.

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FELLOWSHIPS: Available appointments pay up to \$15,000 plus out-of-state tuition for calendar year.

● CURRENT FACULTY AND RESEARCH INTERESTS ●

D. K. ANDERSON, Chairman

Ph.D., University of Washington
Transport Phenomena, Biomedical Engineering, Cardiovascular Physiology, Diffusion in Polymers

D. BRIEDIS

Ph.D., Iowa State University
Biomedical Engineering, Thermodynamics of Living Systems, Biorheology, Mass Transfer in Biological Mineralization

R. E. BUXBAUM

Ph.D., Princeton University
Chemical Engineering Aspects of Nuclear Fusion, Diffusivities and Separation Rates from Theory and Experiment.

C. M. COOPER

Sc.D., Massachusetts Institute of Technology
Thermodynamics and Phase Equilibria, Modeling of Transport Processes

A. L. DeVERA

Ph.D., University of Notre Dame
Chemical and Catalytic Reaction Engineering, Transport Properties of Random Heterogeneous Media, Applied Mathematics, Catalytic Gasification of Carbon, Shape Selectivity Reactions on Zeolites

E. A. GRULKE

Ph.D., Ohio State University
Food Engineering, Membranes Separations, and Polymer Engineering

M. C. HAWLEY

Ph.D., Michigan State University
Kinetics, Catalysis, Reactions in Plasmas, and Reaction Engineering

K. JAYARAMAN

Ph.D., Princeton University
Simplification of Process Models, Parameter Estimation, Rheology of Suspensions and Polymers

D. J. MILLER

Ph.D., University of Florida
Catalytic Reaction Kinetics and Catalyst Characterization, Gas-Solid Reactions, and Modeling of Stochastic Processes

C. A. PETTY

Ph.D., University of Florida
Fluid Mechanics, Turbulent Transport Phenomena, Solid-Fluid Separations

B. W. WILKINSON

Ph.D., Ohio State University
Energy Systems and Environmental Control, Nuclear Reactor, and Radioisotope Applications

FOR ADDITIONAL INFORMATION WRITE

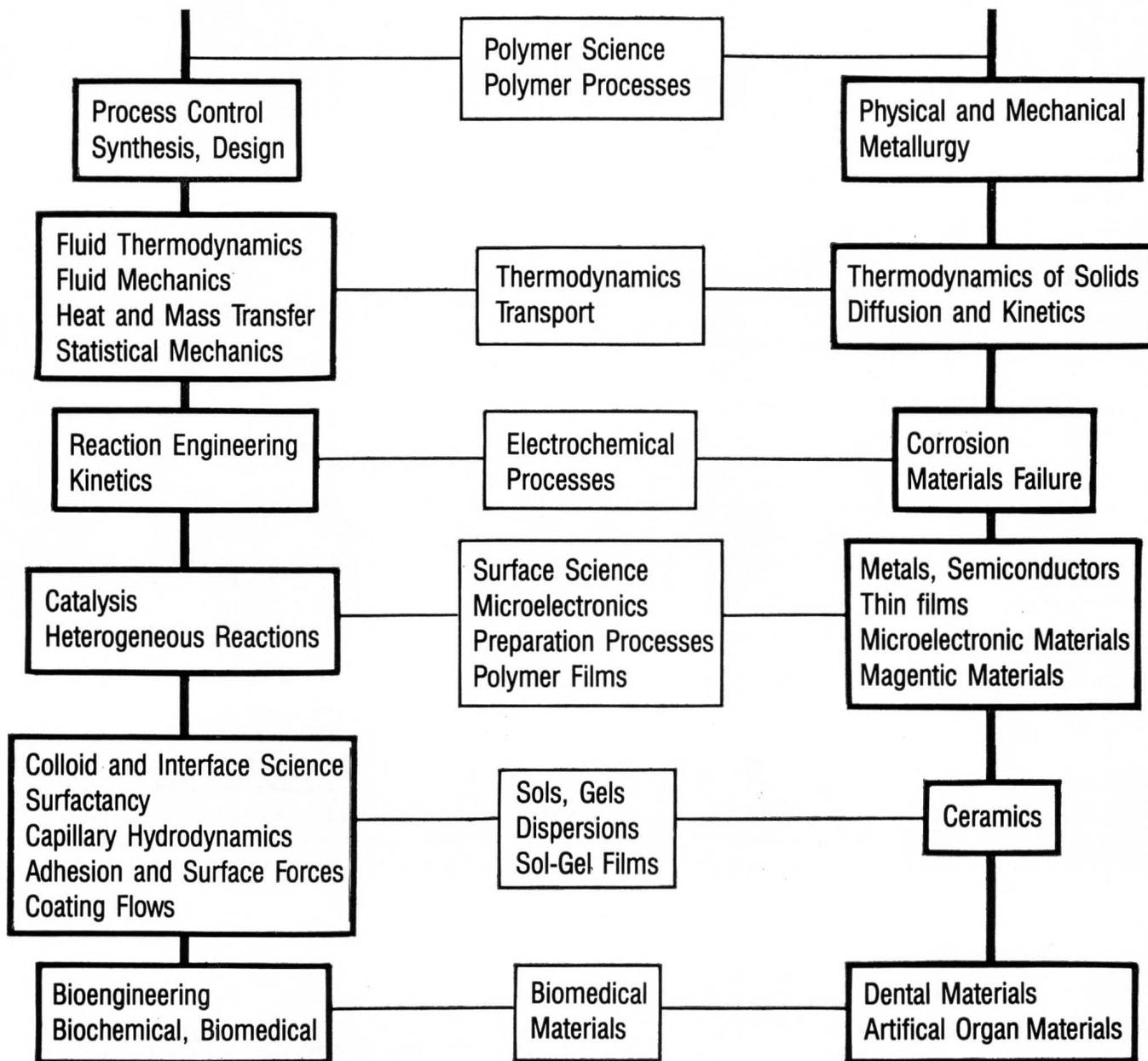
**Dr. Donald K. Anderson, Chairman, Department of Chemical Engineering
173 Engineering Building, Michigan State University
East Lansing, Michigan 48824-1226**

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Chemical Engineering Program

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D.F. Evans	C.W. Macosko	R.W. Staehle
A. Franciosi	M.E. Nicholson	M.V. Tirrell
A.G. Frederickson	R.A. Oriani	J.H. Weaver
C.J. Geankoplis		S.T. Wellinghoff

For information and application forms, write:

Graduate Admissions
Chemical Engineering and
Materials Science
University of Minnesota
421 Washington Ave. S.E.
Minneapolis, MN. 55455

Department of Chemical Engineering

UNIVERSITY OF MISSOURI — ROLLA

ROLLA, MISSOURI 65401

Contact Dr. J. W. Johnson, Chairman

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

FACULTY AND RESEARCH INTERESTS

D. AZBEL (D.Sc., Mendeleev ICT-Moscow)—Dispersed Two-Phase Flow, Coal Gasification and Liquefaction.

N. L. BOOK (Ph.D., Colorado)—Computer Aided Process Design, Bioconversion.

O. K. CROSSER (Ph.D., Rice)—Transport Properties, Kinetics, Catalysis.

M. E. FINDLEY (Ph.D., Florida)—Biochemical Studies, Biomass Utilization

J.-C. HAJDUK (Ph.D. Illinois-Chicago)—Chemical kinetics, Statistical and Non-equilibrium Thermodynamics.

J. W. JOHNSON (Ph.D., Missouri)—Electrode Reactions, Corrosion.

A. I. LIAPIS (Ph.D., ETH-Zurich)—Adsorption, Freeze Drying, Modeling, Optimization, Reactor Design.

J. M. D. MAC ELROY (Ph.D., University College Dublin)—Transport Phenomena, Heterogeneous Catalysis, Drying, Statistical Mechanics.

D. B. MANLEY (Ph.D., Kansas)—Thermodynamics, Vapor-Liquid Equilibrium.

P. NEOGI (Ph.D., Carnegie-Mellon)—Interfacial Phenomena

G. K. PATTERSON (Ph.D., Missouri-Rolla)—Turbulence, Mixing, Mixed Reactors, Polymer Rheology.

B. E. POLING (Ph.D., Illinois)—Kinetics, Energy Storage, Catalysis.

X. B. REED, JR. (Ph.D., Minnesota)—Fluid Mechanics, Drop Mechanics, Coalescence Phenomena, Liquid-Liquid Extraction, Turbulence Structure.

O. C. SITTON (Ph.D., Missouri-Rolla)—Bioengineering

R. C. WAGGONER (Ph.D., Texas A&M)—Multi-stage Mass Transfer Operations, Distillation, Extraction, Process Control.

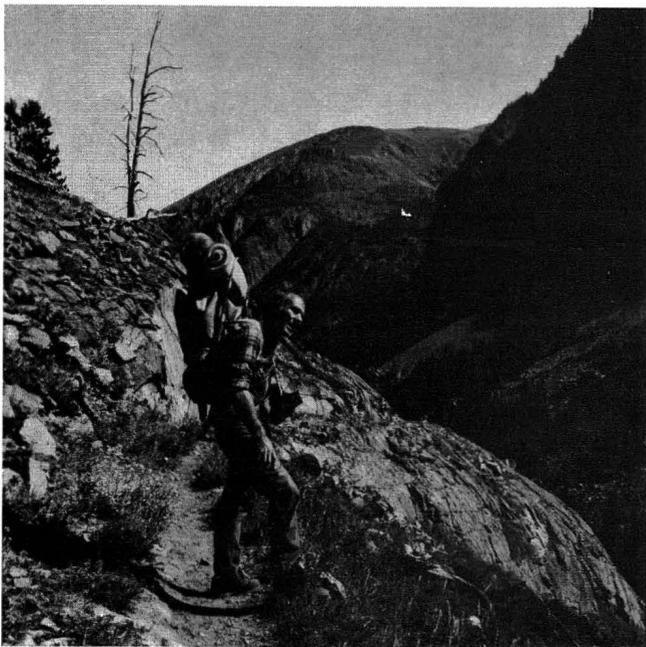
H. K. YASUDA (Ph.D., New York-Syracuse)—Polymer Membrane Technology, Thin-Film Technology, Plasma Polymerization, Biomedical Materials.



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

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- Energy** — **coal liquifaction, heavy oil up-grading, biomass conversion**
- Catalysis** — **surface science, catalyst poisoning, mass transfer**

Financial support is available

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Graduate Coordinator
Chemical Engineering Department
Montana State University
Bozeman, Montana 59717

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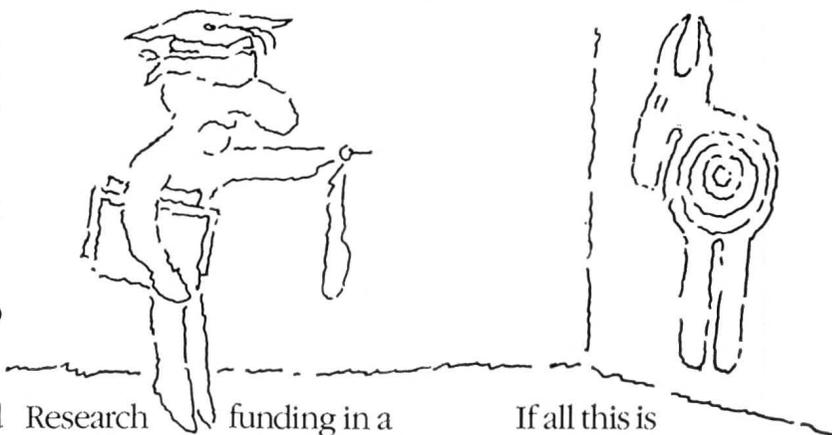
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Write to our department head, Harold B. Hopfenberg, for more information. Or call him at (919) 737-2318.

After all, when you're trying to make a decision on a graduate school, it always pays to do your homework.

CHEMICAL ENGINEERING NORTH CAROLINA STATE UNIVERSITY

Department of Chemical Engineering, Box 5035, North Carolina State University, Raleigh, NC 27650

Chemical Engineering at

Northwestern University

S. George Bankoff

Two-phase heat transfer, fluid mechanics

George M. Brown

Thermodynamics of multicomponent phase equilibria

John B. Butt

Chemical reaction engineering

Stephen H. Carr

Solid state properties of polymers

William C. Cohen

Control and measurement of distributed parameter systems

Buckley Crist Jr.

Polymer science

Joshua S. Dranoff

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Thomas K. Goldstick

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Hugh M. Hulburt

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Harold H. Kung

Kinetics, heterogeneous catalysis

Chung K. Law

Combustion

Richard S.H. Mah

Computer-aided process planning, design and analysis, distillation systems

Gregory Ryskin

Fluid mechanics, computational methods, polymeric liquids

Wolfgang M.H. Sachtler

Heterogeneous catalysis

John C. Slattery

Interfacial transport phenomena, multiphase flows

William F. Stevens

Process control and optimization/computer applications

George Thodos

Physical properties of gases and liquids

John M. Torkelson

Polymer science



**For information and application to the
graduate program, write**

John B. Butt
Chairman of Graduate Program
Department of Chemical Engineering
Northwestern University
Evanston, Illinois 60201

The Ohio State University

Chemical Engineering

THE OHIO STATE UNIVERSITY has offered graduate degrees in Chemical Engineering since just after the turn of the century and has a proud tradition of distinguished alumni in industry, government and academic positions.

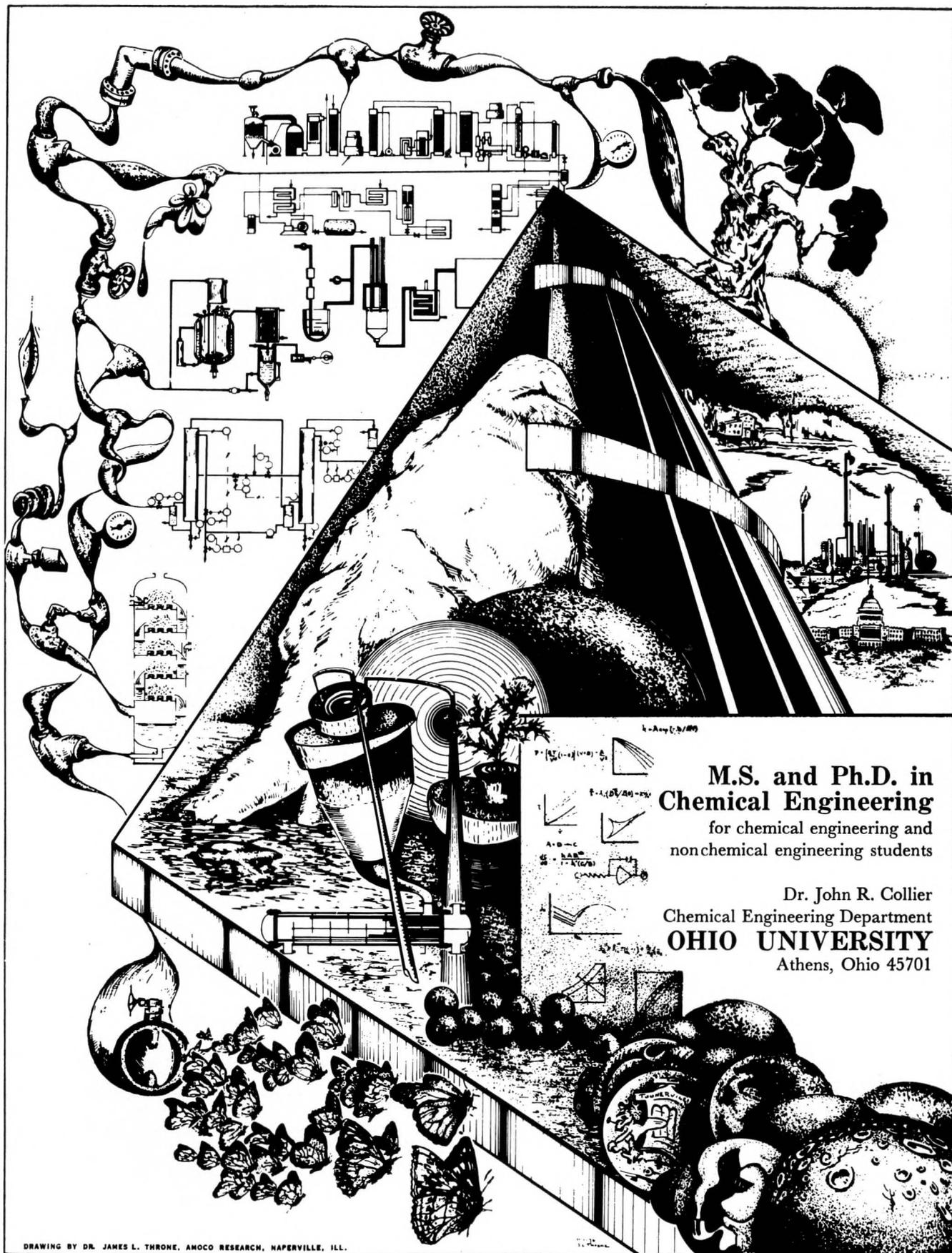
The requirements for both the M.S. and the Ph.D. degree include a core of basic chemical engineering courses and other courses appropriate to the student's research and professional goals. Because research is such a vital part of graduate education, close relationships between research advisors and students are fostered. The Department has fourteen faculty members and the range of research topics and/or course option areas cover a wide cross section of chemical engineering theory and practice:

Biochemical Engineering	Bioengineering
Coal Conversion and Treatment	Combustion of Materials
Digital Process Control	Environmental
Fluidized Bed	Fluid Mechanics
Heat Transfer	Kinetics
Mass Transfer	Petroleum Reservoir
Polymer Processing	Process Design
Process Simulation	Rheology
Separation Processes	Thermodynamics
Turbulence	

The Chemical Engineering Building has more than 80,000 square feet and includes 45 research and teaching laboratories and classrooms. The Department has a DEC VAX 11/780 computer for data acquisition, computation, and process control services. More than fifteen interactive graphics terminals are available for research and teaching. Many kinds of specialized research equipment are available along with a University computer and an extensive library with fine search capabilities.

COLUMBUS is a center for technical activity with Battelle Memorial Institute and Chemical Abstracts adjacent to the campus and many corporate research centers and technically-based industries nearby. Cultural offerings in music, art and drama are also widely available in Columbus. For those interested in recreational activities, the University offers opportunities for virtually every sport from archery to water skiing.

For further information, write to Prof. Jacques L. Zakin, Dept. of Chemical Engineering, 140 W. 19th Street, The Ohio State University, Columbus, Ohio 43210.



DRAWING BY DR. JAMES L. THRONE, AMOCO RESEARCH, NAPERVILLE, ILL.

**M.S. and Ph.D. in
Chemical Engineering**
for chemical engineering and
nonchemical engineering students

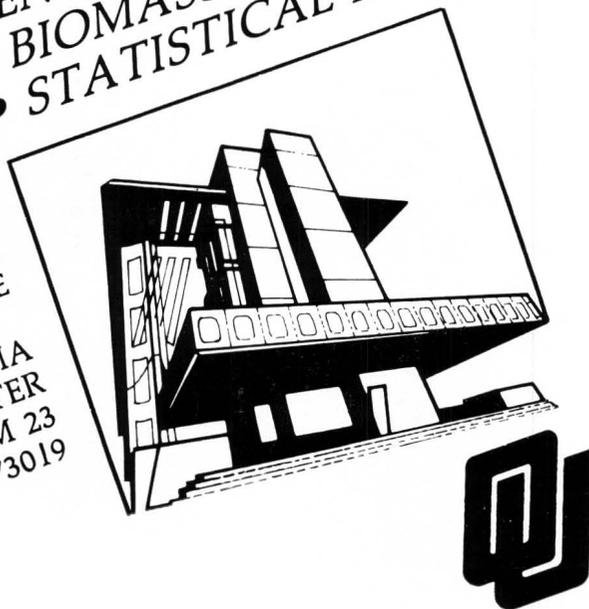
Dr. John R. Collier
Chemical Engineering Department
OHIO UNIVERSITY
Athens, Ohio 45701

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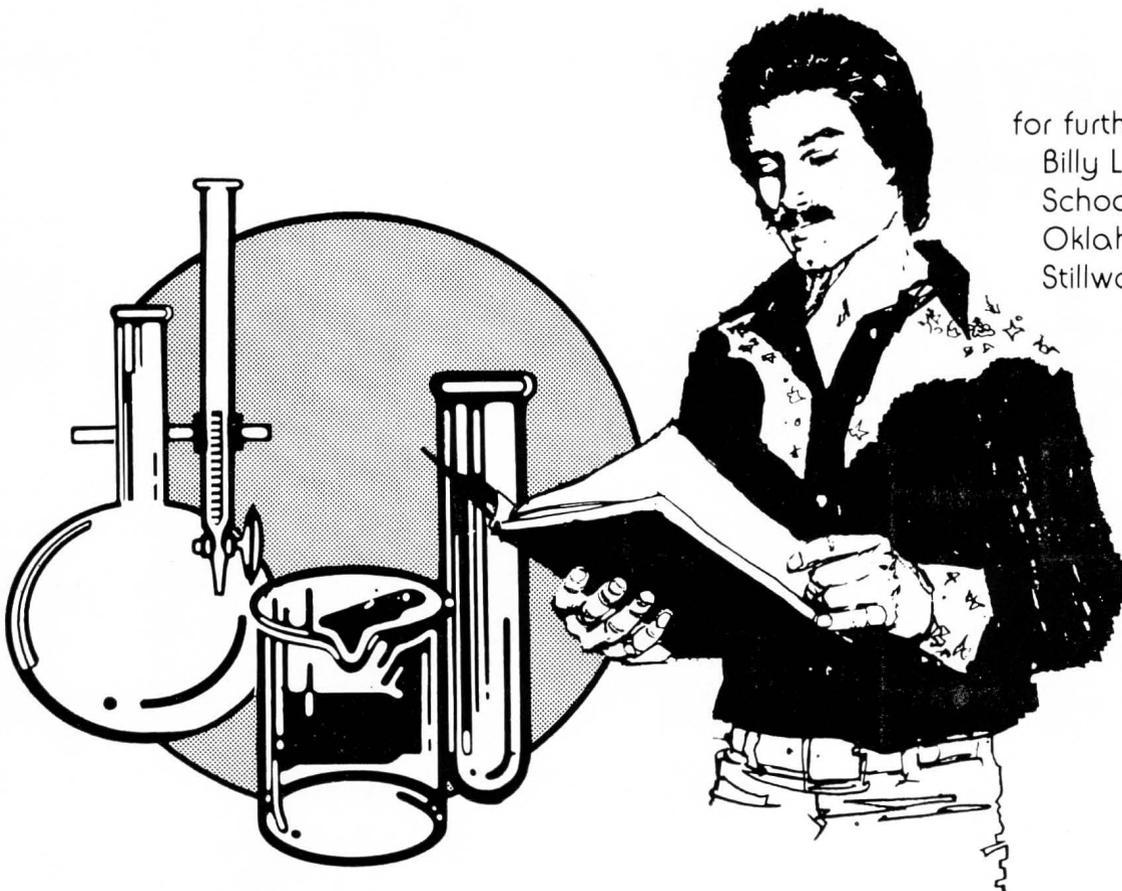
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NORMAN, OKLAHOMA 73019



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for further information write to:
Billy L. Crynes, Head
School of Chemical Engineering
Oklahoma State University
Stillwater, Oklahoma 74078



The Oklahoma State University Chemical Engineering faculty:

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Dr. Kenneth J. Bell
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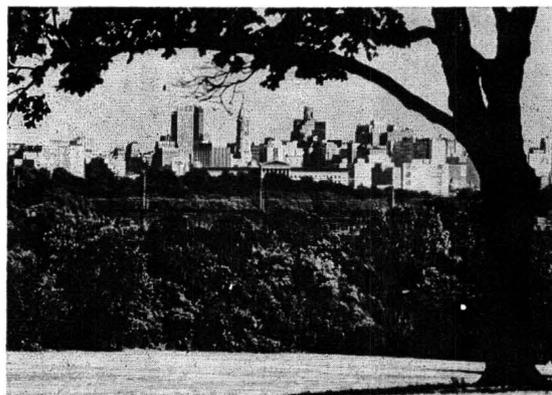
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Biochemical Engineering
Biomedical Engineering
Chemical Reactor Engineering
Combustion
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Crystal Growth
Electrochemistry
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FACULTY

Stuart W. Churchill, PhD, Michigan (1952)
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Raymond J. Gorte, PhD, Minnesota (1981)
David J. Graves, ScD, MIT (1967)
A. Norman Hixson, Emeritus
Douglas A. Lauffenburger, PhD, Minnesota (1979)
Mitchell Litt, D Eng Sci., Columbia (1961)
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Melvin C. Molstad, Emeritus
Daniel D. Perlmutter, PhD, Yale (1956)
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Director of Graduate Admissions
Department of Chemical Engineering
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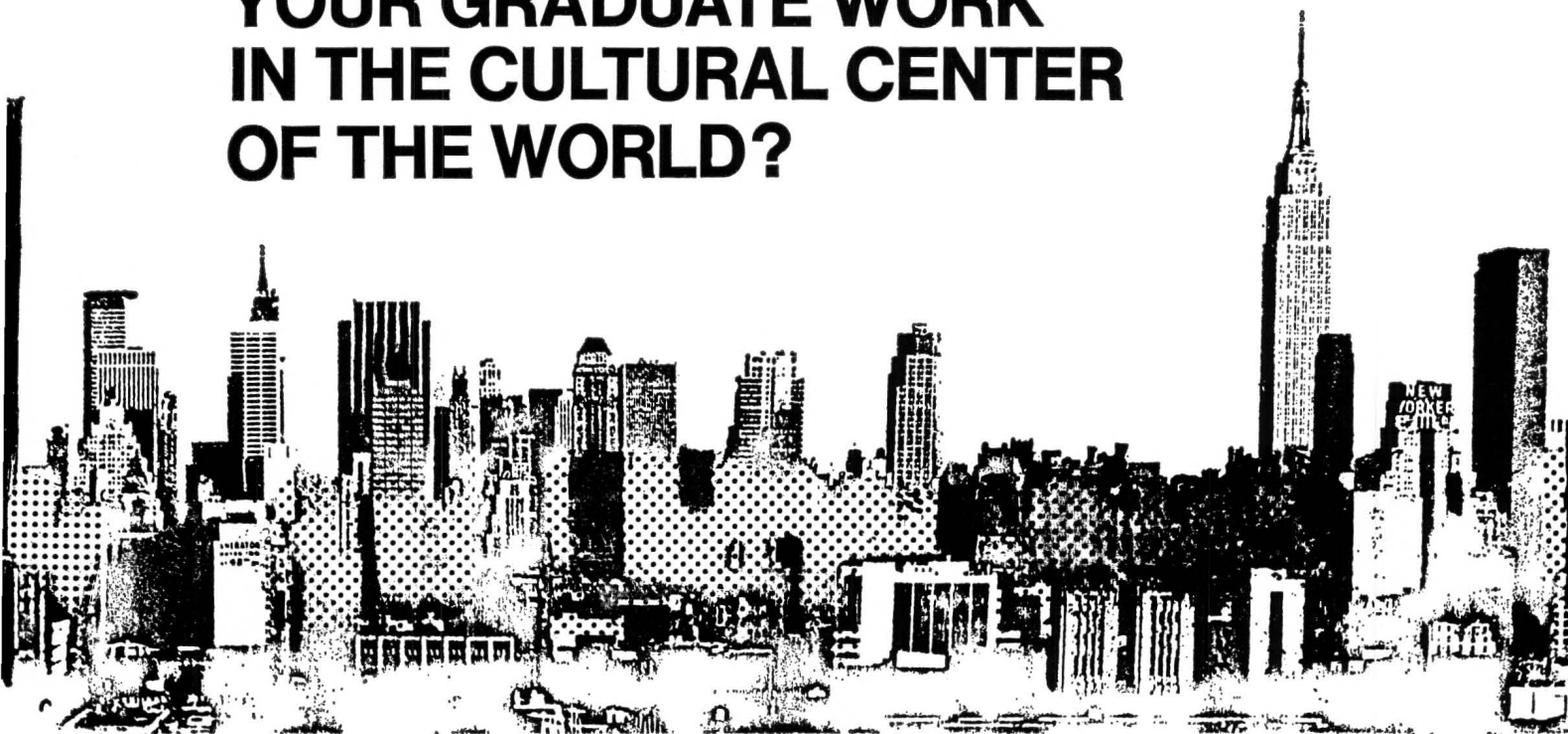
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Dr. J. Larry Duda, Head
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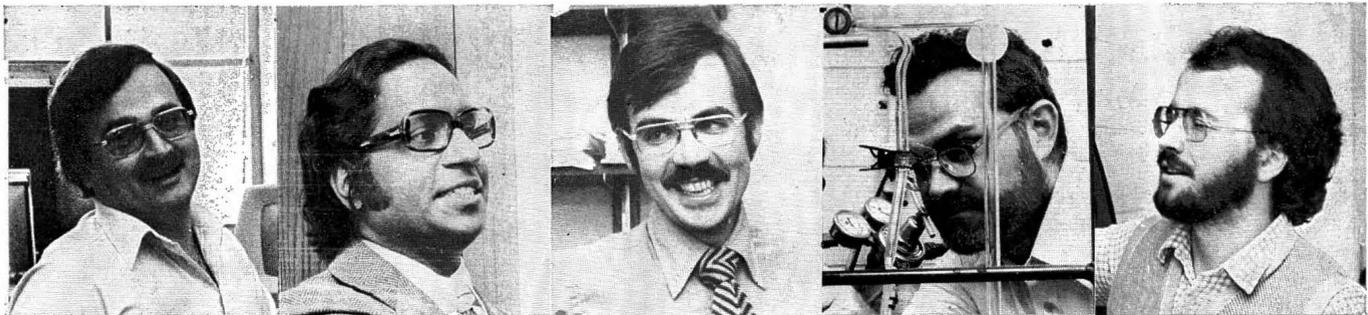
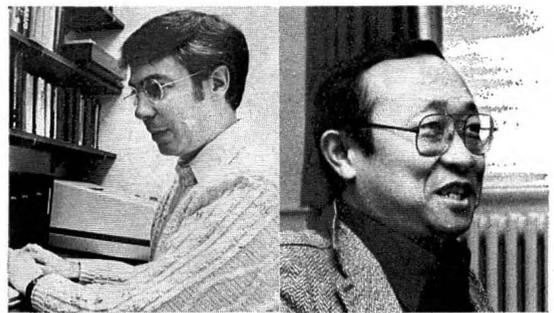
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Graduate Information
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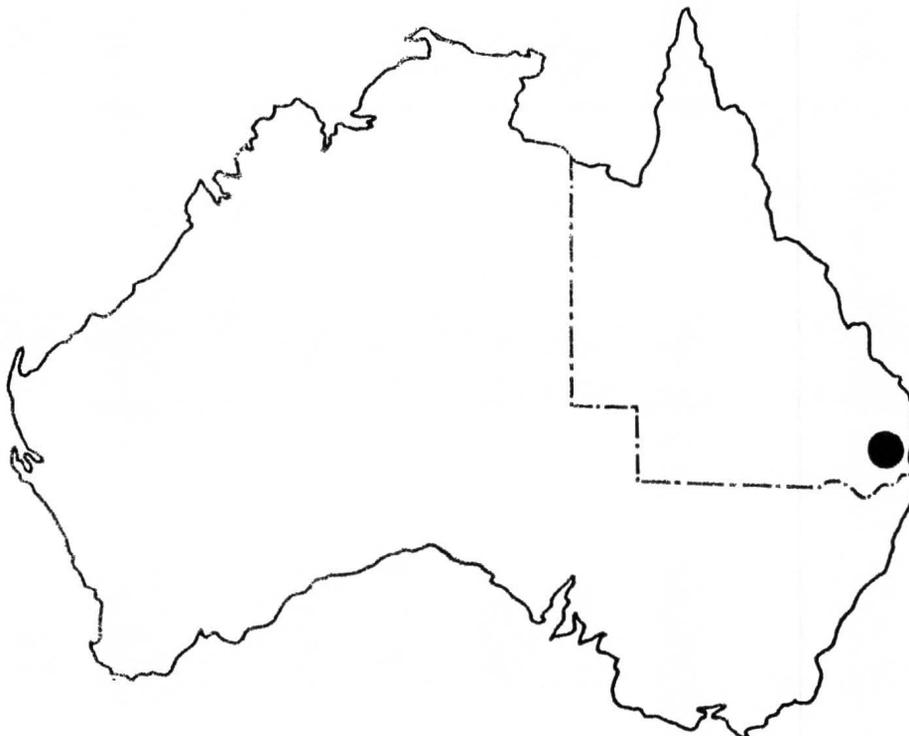
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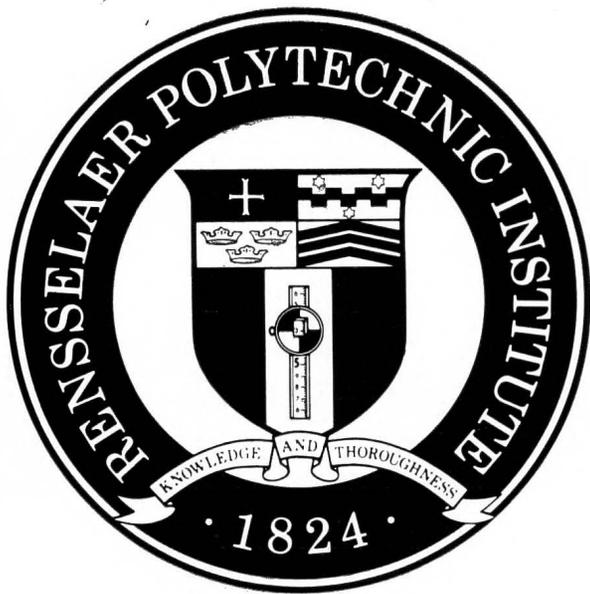
THE DEPARTMENT

The Department occupies its own building, is well supported by research grants, and maintains an extensive range of research equipment. It has an active postgraduate programme, which involves course work and research work leading to M.Eng. Studies, M.Eng.Science and Ph.D.degrees.

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For further information write to: Co-ordinator of Graduate Studies, Department of Chemical Engineering, University of Queensland, Brisbane, Qld. 4067 AUSTRALIA.



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

Department Faculty and Areas of Research

Michael M. Abbott Ph.D. (Rensselaer)—thermodynamics; phase equilibria.

Elmar R. Altwicker Ph.D. (Ohio State)—air pollution control; atmospheric chemistry and deposition; mass transfer with chemical reaction.

Yaman Arkun Ph.D. (Minnesota)—process design, dynamics, and control.

Donald B. Aulenbach P.E., Ph.D. (Rutgers)—heavy metals removal; chemical interactions in fresh-water lakes and streams; disposal of radioactive wastes.

Georges Belfort Ph.D. (California-Irvine)—separations engineering (membrane processes and adsorption); biochemical concentration and reactors; particle dynamics; adsorption thermodynamics.

Henry R. Bungay III P.E., Ph.D. (Syracuse)—oxygen transfer in various microbial systems; high flow rate continuous cultures; biomass refining.

Chan I. Chung Ph.D. (Rutgers)—engineering aspects of polymer processing; physics of the structure-property relationships of polymer melts.

Nicholas L. Clesceri Ph.D. (Wisconsin)—intermedia transport research; acid precipitation; toxic heavy metals removal; water supply taste/odor problems; lake eutrophication.

Dady B. Dadyburjor Ph.D. (Delaware)—heterogeneous catalysis: deactivation, regeneration, and effects of catalyst microstructure; aggregation of surface active agents.

Arthur Fontijn D.Sc. (Amsterdam)—High temperature reaction kinetics; combustion; luminescence measurements; trace gas detection.

Cynthia S. Hirtzel Ph.D. (Northwestern)—extreme value phenomena, theory and applications; stochastic processes in engineering science.

Arland H. Johannes P.E., Ph.D. (Kentucky)—acid precipitation; wet and dry deposition; surface studies of coal mineral matter.

Clement Kleinstreuer Ph.D. (Vanderbilt)—non-isothermal fluid-particle systems; higher-order boundary layer theory; membrane separation systems, biochemical reactor design.

Peter K. Lashmet P.E., Ph.D. (Delaware)—process engineering; development of design procedures.

Howard Littman Ph.D. (Yale)—Fluid-particle systems with emphasis on the mechanics of spouted beds.

Morris H. Morgan III Ph.D. (Rensselaer)—reaction engineering with emphasis on spouted bed systems; theoretical and experimental investigations of fluid-particle systems.

Charles Muckenfuss Ph.D. (Wisconsin)—theoretical studies of transport phenomena; applications of kinetic theory and irreversible thermodynamics.

E. Bruce Nauman Ph.D. (Leeds)—polymer reaction engineering; study of motionless mixers in tubular polymerizers; residence time theory—extensions to nonisothermal nonhomogeneous reactors.

Michael H. Peters Ph.D. (Ohio State)—aerosol dynamics; multiphase transport phenomena; statistical physics of fluid-particle systems.

Raj Rajagopalan Ph.D. (Syracuse)—colloidal and interfacial phenomena; statistical physics and thermodynamics of macromolecular systems; transport phenomena.

William W. Shuster P.E., D.Ch.E. (Rensselaer)—treatment and disposal of hazardous wastes; evaporation of toxic organics; methane production from anaerobic decomposition.

Sanford S. Sternstein Ph.D. (Rensselaer)—engineering and mechanical properties of polymers and polymeric materials; inhomogeneous swelling theory; high performance composites.

Hendrick C. VanNess P.E., D.Eng. (Yale)—solution thermodynamics; vapor/liquid equilibrium; heat-of-mixing collection; correlation.

Peter C. Wayner Jr. Ph.D. (Northwestern)—change of phase heat transfer; interfacial phenomena; transport processes in thin liquid.

Financial Support:

Full time graduate students are eligible for financial support including tuition remission and tax-free fellowships

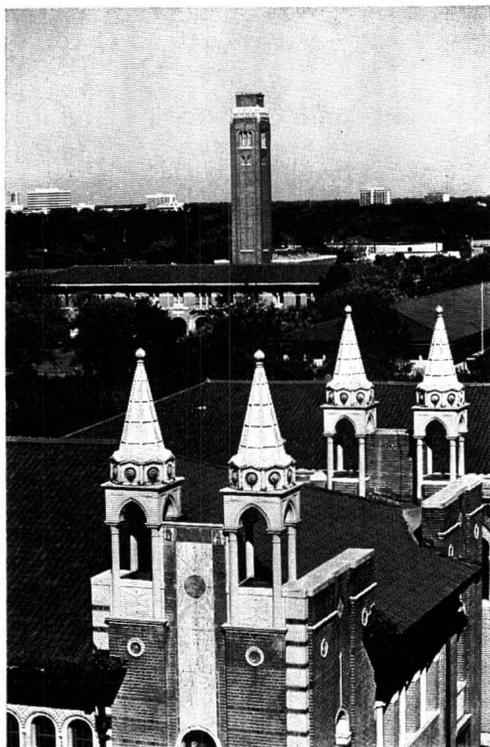
Applications and Information:

For full details, write:

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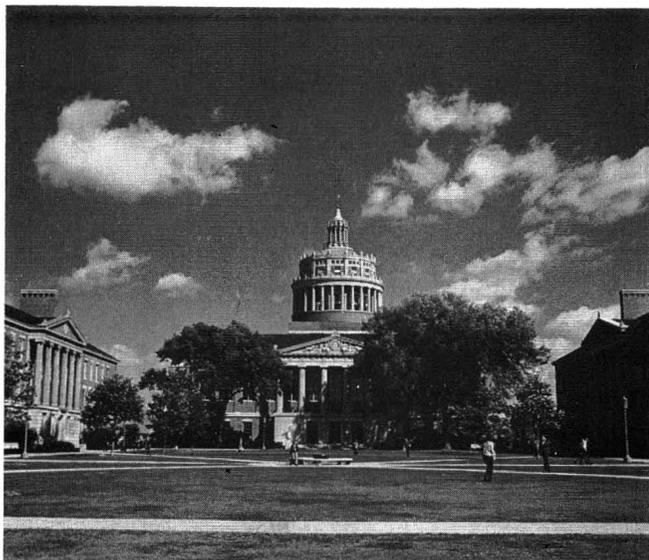
THE FACULTY

- WILLIAM W. AKERS (Michigan, 1950)
Vice-president for administration.
- CONSTANTINE D. ARMENIADES (Case Western Reserve, 1969) Polymer science, polymers and composites, biomaterials, and light scattering.
- SAM H. DAVIS, JR. (MIT, 1957) Dynamics of chemical systems, optimization, and process control.
- DEREK C. DYSON (London, 1966) Interfacial phenomena, hydrodynamic stability, and enhanced oil recovery.
- J. DAVID HELLUMS (Michigan, 1961) Fluid mechanics and biomedical engineering.
- JOE W. HIGHTOWER (Johns Hopkins, 1963) Kinetics and heterogeneous catalysis.
- RIKI KOBAYASHI (Michigan, 1951)
Thermodynamics and transport properties, chromatography, coal liquefaction, and high-pressure properties.
- THOMAS W. LELAND, JR. (Texas, 1954)
Thermodynamic properties.
- LARRY V. McINTIRE (Princeton, 1970) Rheology, fluid mechanics, and biomedical engineering.
- CLARENCE A. MILLER (Minnesota, 1969)
Interfacial phenomena in enhanced oil recovery.
- E. TERRY PAPOUTSAKIS (Purdue, 1979)
Biochemical engineering and applied mathematics.
- RICHARD L. ROWLEY (Michigan State, 1978)
Measurement and prediction of thermodynamic and transport properties; nonequilibrium thermodynamics.
- KYRIACOS ZYGOURAKIS (Minnesota, 1981)
Chemical reaction engineering, computer applications for control and data acquisition.

APPLICATIONS

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For further information and applications, contact:

Professor John C. Friedly, Chairman
Department of Chemical Engineering
University of Rochester
Rochester, New York 14627
Phone: (716) 275-4042

Faculty and Research Areas

S. H. CHEN, Ph.D. 1981, Minnesota
Mass Transfer, Thermodynamics, Homogeneous Catalysis

E. H. CHIMOWITZ, Ph.D. 1982, Connecticut
Computer-Aided Design, Super-Critical Extraction, Control

G. R. COKELET, Sc.D. 1963, M.I.T.
Blood and Suspension Rheology, Biotechnology

R. F. EISENBERG, M.S. 1948, Rochester
Corrosion, Physical Metallurgy

M. R. FEINBERG, Ph.D. 1968, Princeton
Complex Reaction Systems, Continuum Mechanics

J. R. FERRON, Ph.D. 1958, Wisconsin
Molecular Transport Processes, Applied Mathematics

J. C. FRIEDLY, Ph.D. 1965, Calif. (Berkeley)
Process Dynamics, Control, Cryogenics

R. H. HEIST, Ph.D. 1972, Purdue
Nucleation, Solid State, Atmospheric Chemistry

J. JORNE, Ph.D. 1972, Calif. (Berkeley)
Electrochemical Engineering, Theoretical Biology

R. H. NOTTER, M.D., Ph.D. 1969, Washington (Seattle)
Pulmonary Surfactants, Lung Toxicology

H. J. PALMER, Ph.D. 1971, Washington (Seattle)
Interfacial Phenomena, Mass Transfer

H. SALTSBURG, Ph.D. 1955, Boston
Surface Phenomena, Catalysis, Molecular Scattering

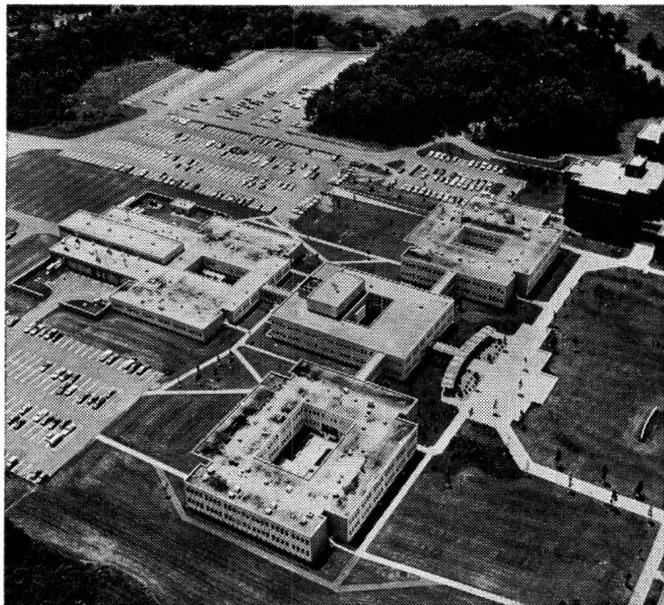
S. V. SOTIRCHOS, Ph.D. 1982, Houston
Reaction Engineering, Combustion and Gasification of Coal, Gas-Solid Reactions

G. J. SU, Sc.D. 1937, M.I.T.
Colloidal and Amorphous States, Glass Science



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

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

F.A. Gadala-Maria, Assistant Professor, Ph.D., Stanford University, 1979 (Fluid mechanics, rheology).

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

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

T.G. Stanford, Assistant Professor, Ph.D., The University of Michigan, 1977 (Chemical reactor engineering, mathematical modeling of chemical systems, process design, thermodynamics).

V. Van Brunt, Associate Professor, Ph.D., University of Tennessee, 1974 (Mass transfer, computer modeling, fluidization).

For further information contact:

Prof. J.H. Gibbons
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College of Engineering
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Department of Chemistry and Chemical Engineering

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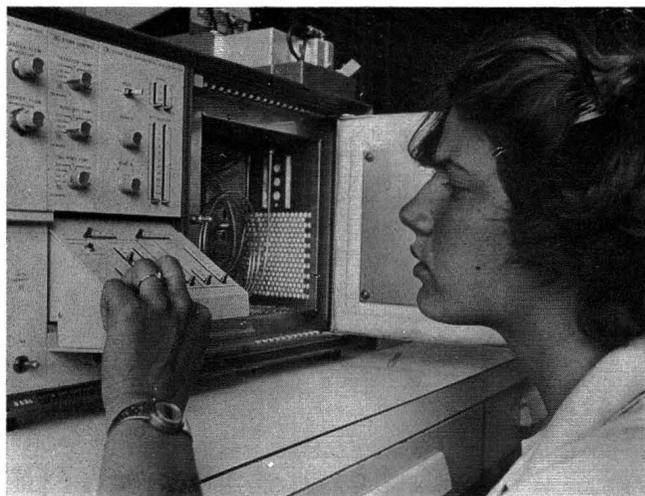
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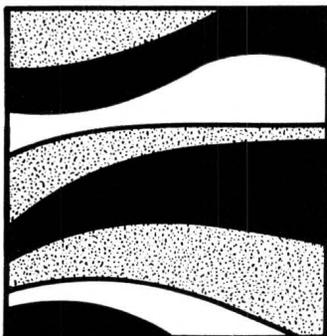
For Information write:

*Lawrence L. Tavlarides, Chairman
Department of Chemical Engineering
and Materials Science
Syracuse University
229 Hinds Hall
Syracuse, New York, 13210*

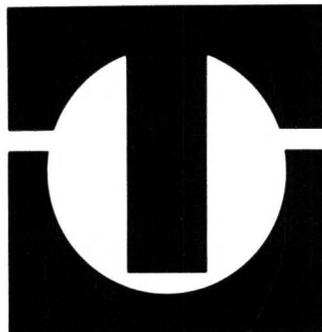
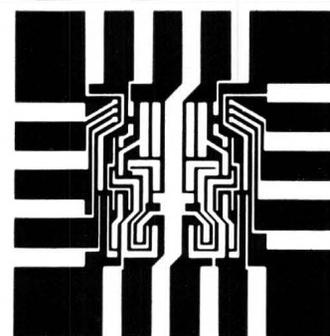
RESEARCH INTERESTS

Allen J. Barduhn	Desalination
John C. Heydweiller	Computational Methods, Simulation
Vasilios Karagounis	Process Control, Electrochemistry
George C. Martin	Polymer Properties and Applications
Phillip A. Rice	Bitransport Phenomena
Ashok Sangani	Theoretical Fluid Mechanics
James A. Schwarz	Catalysis, Surface Phenomena
S. Alexander Stern	Membrane Processes
Lawrence L. Tavlarides	Multiphase Reaction Systems
Chi Tien	Fluid Particle Separation
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with listing of degree(s), date(s), and grade point average(s) to
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Chemical, Metallurgical,
and Polymer Engineering
The University of Tennessee
Knoxville, Tennessee 37996-2200

Faculty

William T. Becker
Donald C. Bogue
Charlie R. Brooks
Duane D. Bruns
Edward S. Clark
Robert M. Counce
John F. Fellers
George C. Frazier
John M. Holmes
Hsien-Wen Hsu
Homer F. Johnson
Department Head
Carl D. Lundin
Charles F. Moore
Ben F. Oliver
Joseph J. Perona
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for Chemical Engineering
Joseph E. Spruiell
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for Materials Engineering
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● RESEARCH INTERESTS ●

Aerosol Physics & Chemistry
Air Pollution Science
Artificial Internal Organs
Aqueous Mass Transfer
Biomass Liquefaction
Biomedical Engineering
Catalysis
Chemical Engineering Education
Coal Beneficiation
Coal Desulfurization
Coal Gasification & Combustion
Computer Applications
Computer-Based Education
Colloid Science
Crystal Structure & Properties
Energy Applications
Enhanced Oil Recovery
Heat Transfer
Material Science
Membrane Science
Multi-phase Systems
Optimization
Polymer Applications
Polymer Processing
Polymer Properties
Polymer Thermodynamics
Process Control
Process Design & Development
Process Simulation
Reaction Kinetics & Mechanisms
Separation Processes
Stack Gas Desulfurization
Surface Science
Thermodynamics
Transition Metal Studies

Inquiries should be sent to

Graduate Advisor
Department of Chemical Engineering
The University of Texas
Austin, TX 78712



TEXAS A&M UNIVERSITY

Texas A&M is a land-grant and sea-grant university, and the oldest public institution of higher learning in Texas. The current enrollment is about 35,000. The university location is Bryan/College Station, Texas—twin cities with a combined population of 122,000 (including students). The surrounding country is deciduous forest—Houston is 95 miles Southeast and Dallas is 160 miles North.

CHEMICAL ENGINEERING DEPARTMENT

The ChE department has an enrollment of about 1000 undergraduates and 90 graduates. ChE has excellent facilities in the Zachry Engineering Center. All graduate students have desk space. Graduate stipends are currently \$1050/month for teaching assistantships and \$900/month for research assistants.

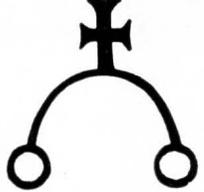
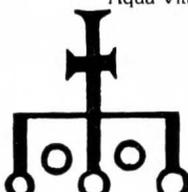
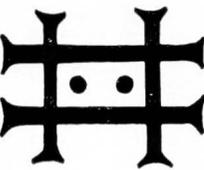
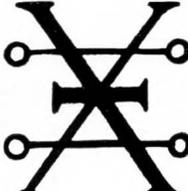
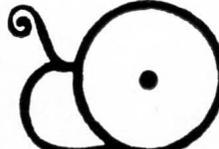
Admission to The Texas A&M University System and any of its sponsored programs is open to qualified individuals regardless of race, color, age, religion, sex, national origin or educationally unrelated handicaps.

FACULTY AND RESEARCH INTERESTS

C. D. Holland (department head)—distillation
A. Akgerman—kinetics
R. G. Anthony—catalysis
D. B. Bukur—reaction engineering
J. A. Bullin—gas sweetening, air pollution
R. Darby—rheology
R. R. Davison—solar energy
L. D. Durbin—process control
P. T. Eubank—thermodynamics
T. W. Fogwell—applied mathematics
A. M. Gadalla—catalyst characterization
C. J. Glover—polymer solutions
K. R. Hall—thermodynamics
D. T. S. Hanson—biochemical
W. B. Harris—methanol fuel
J. C. Holste—thermodynamics
G. B. Tatterson—turbulence and mixing
A. T. Watson—porous media
R. E. White—electrochemical applications

FOR INFORMATION CONTACT:

**Graduate Advisor
Chemical Engineering Dept.
Texas A&M University
College Station, TX 77843
409/845-3361**

Eggshells 	Amalgam 
Cinnabar 	Vinegar 
Vitriol 	Lime 
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applying chemistry to the needs of man.

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chemical and microbiological processing,
chemicals from renewable resources

Coal Science and Process Chemistry

chemistry of prompt intermediates, reaction paths
in coal liquefaction, fate of trace elements

Coal Combustion Workshop

small-scale systems, fate of trace elements,
environmental controls, fluidized beds

Microcomputers, Digital Electronics, and Control

digital process measurements, microcomputer
interfacing, remote data acquisition, digital controls

Polymer Science and Engineering

processing, morphology, synthesis, surface science,
biopolymers

Engineering Chemistry

chemically pumped lasers, multiphase catalysis,
chemical microengineering, photoelectrochemistry
reactor design

Biochemical Engineering

synthetic foods, antibiotics, fermentation
process design and instrumentation,
environmental engineering

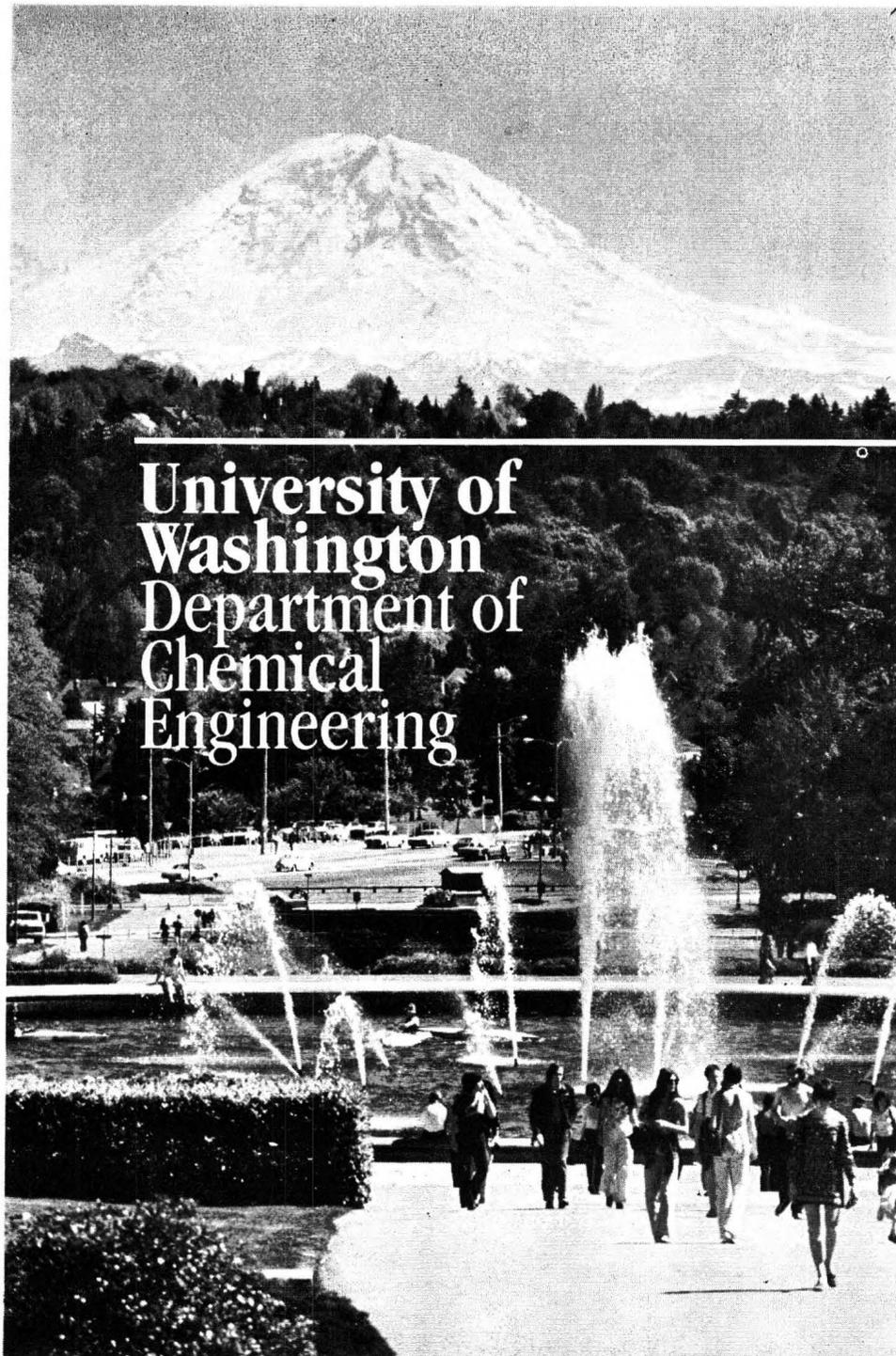
Surface Activity

use of bubbles and other interfaces for separations,
water purification, trace elements, concentration,
understanding living systems

VPI&SU is the state university of Virginia with 20,000 students and over 5,000 engineering students . . . located in the beautiful mountains of southwestern Virginia. White-water canoeing, skiing, backpacking, and the like are all nearby, as are Washington, D. C. and historic Williamsburg.

Initial Stipends to \$10,000 per year.

Write to: Graduate Committee
Chemical Engineering Department, Virginia Polytechnic
Institute and State University, Blacksburg, Virginia
24061, or call collect (703) 961-5771.



University of Washington Department of Chemical Engineering

The Department has excellent research space, instrumentation, computing facilities, and shop support. There are about 50 graduate students of whom typically 6-8 are foreign students and the remainder are from about 30 universities in over 20 States. All full-time graduate students are supported.

The research environment is stimulating and supportive, and there is a fine esprit de corps among the graduate students and faculty. Seattle is a beautiful city with outstanding cultural activities and unparalleled outdoor activities throughout the year.

We welcome your inquiry. For further information please write:

Chairman
Department of Chemical Engineering, BF-10
University of Washington
Seattle, WA 98195

 University of Washington

Regular Faculty

J. Ray Bowen, Ph.D., Stanford
(Dean, College of Engineering)
John C. Berg, Ph.D., Berkeley
E. James Davis, Ph.D., Washington
Bruce A. Finlayson, Ph.D., Minnesota
Harold E. Hager, Ph.D., Princeton
William J. Heideger, Ph.D., Princeton
Eric W. Kaler, Ph.D., Minnesota
Joseph L. McCarthy, Ph.D., McGill
N. Lawrence Ricker, Ph.D., Berkeley
James C. Seferis, Ph.D., Delaware
Charles A. Sleicher, Ph.D., Michigan

Research Faculty

Thomas A. Horbett, Ph.D., Washington
Buddy D. Ratner, Ph.D., Brooklyn Poly

Adjunct and Joint Faculty Active in Department Research

G. Graham Allan, Ph.D., Glasgow
Allan S. Hoffman, Sc.D., M.I.T.
William T. McKean, Ph.D., Washington
Michael J. Pilat, Ph.D., Washington
Kyosti V. Sarkanen, Ph.D., State Univ. N.Y.

Research Areas

Aerosols
Applied Kinetics
Biochemical and Biomedical Engineering
Colloids and Microemulsions
Electrochemical Engineering
Fluid Mechanics and Rheology
Heat Transfer
Mathematical Modeling
Polymer Science and Engineering
Process Control and Optimization
Pulp and Paper Chemistry and Processes
Semiconductor Processing and Technology
Surface Science and Interfacial Phenomena



Washington University

ST. LOUIS, MISSOURI

Washington University encourages and gives full consideration to application for admission and financial aid without respect to sex.

GRADUATE STUDY IN

CHEMICAL ENGINEERING

*MASTER'S AND
DOCTORAL PROGRAMS*

RESEARCH AREAS

Reaction Engineering

Transport Phenomena

Thermodynamics

Process Design
And Control

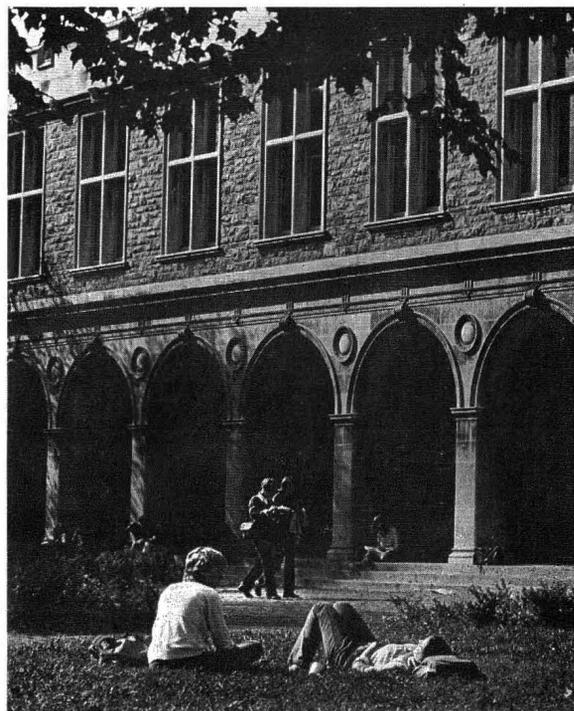
Polymer And
Materials Engineering

Biomedical Engineering

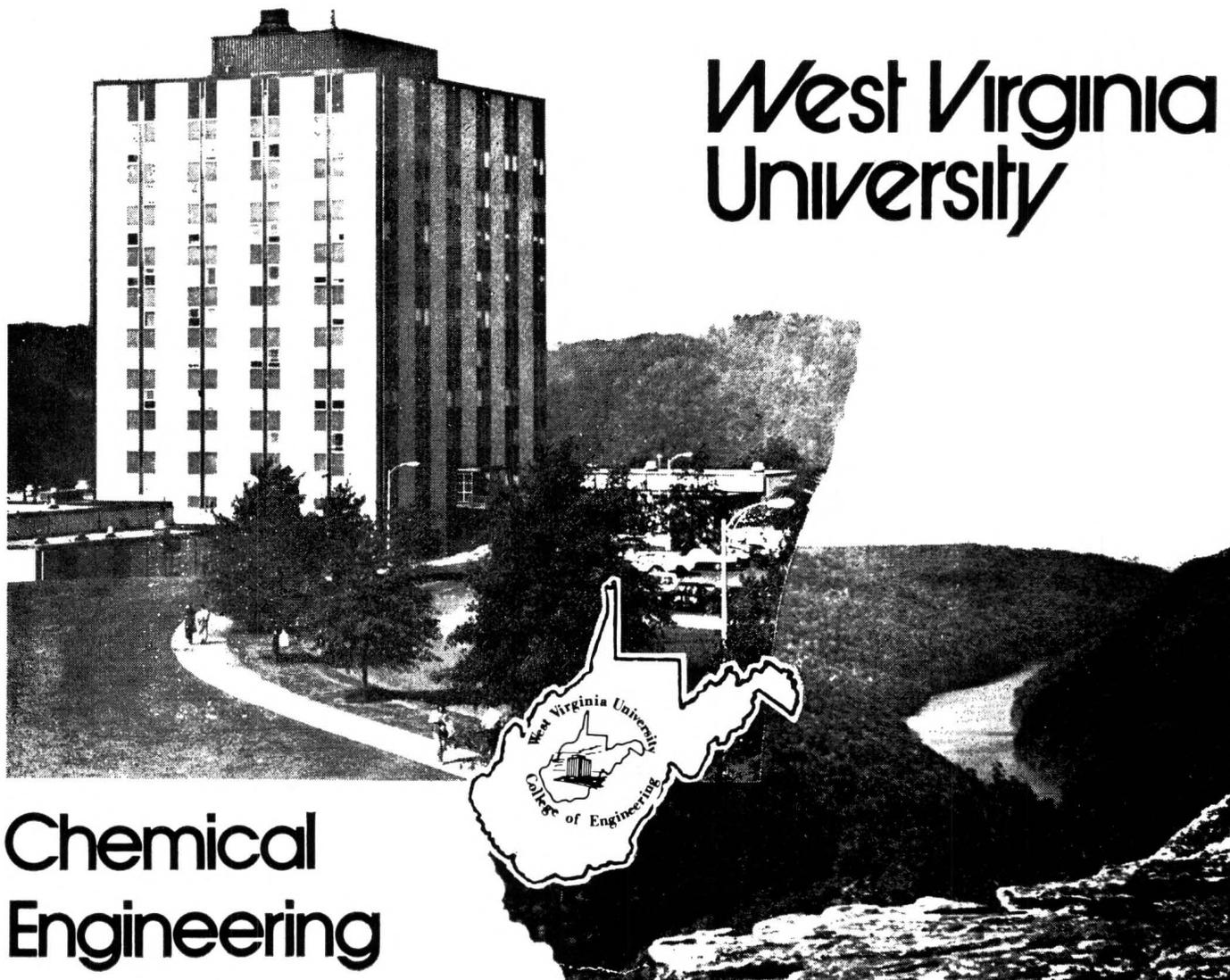
Biochemical Engineering

FOR INFORMATION CONTACT

Graduate Admissions Committee
Department of
Chemical Engineering
Washington University
St. Louis, Missouri 63130



West Virginia University



Chemical Engineering

Faculty

Richard C. Bailie (Iowa State Univ.)
Eugene V. Cilento (Univ. of Cincinnati)
Dady B. Dadyburjor (Univ. of Delaware)
Alfred F. Galli (West Virginia Univ.)
Joseph D. Henry, Jr., Chair. (Univ. of Michigan)
Hisashi Kono (Kyushu Univ.)
Alfred F. Stiller (Univ. of Cincinnati)
Charles White (Univ. of Pennsylvania)
Wallace B. Whiting (Univ. California, Berkeley)
Ray Y. K. Yang (Princeton Univ.)
John W. Zondlo (Carnegie-Mellon Univ.)

Topics

Reaction Engineering
Separation Processes
Surface and Colloid Phenomena
Phase Equilibria
Fluidization
Bioengineering
Solution Chemistry
Transport Phenomena
Biochemical Engineering
Catalysis
Computer-aided design

M.S. and Ph.D. Programs

For further information on financial aid write:

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

Wisconsin

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in Chemical Engineering



Faculty Research Interests

R. Byron Bird:

Transport phenomena, polymer fluid dynamics, polymer kinetic theory

Thomas W. Chapman:

Electrochemistry, mass transfer

Camden A. Coberly:

Director, Engineering Experiment Station

Stuart L. Cooper (Chmn.):

Polymer science, biomaterials

E. Johansen Crosby:

Spray and suspended particle processing

John A. Duffie:

Solar energy

James A. Dumesic:

Kinetics and catalysis, surface chemistry

Charles G. Hill, Jr.:

Kinetics and catalysis, membrane processes

Richard R. Hughes:

Process synthesis, simulation and optimization

Sangtae Kim:

Fluid mechanics, applied mathematics

James A. Koutsky:

Polymer science, adhesives, composites

Stanley H. Langer:

Kinetics, catalysis, electrochemistry, chromatography, hydrometallurgy

E.N. Lightfoot, Jr.:

Mass transport and separation processes; biochemical engineering

W. Robert Marshall:

Director, University-Industry Research Program

Manfred Morari:

Process design, process dynamics and control

W. Harmon Ray:

Process dynamics and control, reactor engineering

Dale F. Rudd:

Process design and industrial development

Glenn A. Sather:

Development of instructional program

Warren E. Stewart:

Reactor modeling, transport phenomena, applied mathematics

Emeritus faculty:

Roger J. Altpeter, Olaf A. Hougen, Wayne K. Neill, Roland A. Ragatz, Charles C. Watson

For further information about graduate study in chemical engineering, write:

The Graduate Committee
Department of Chemical Engineering
University of Wisconsin-Madison
1415 Johnson Drive
Madison, Wisconsin 53706



UNIVERSITY OF ARKANSAS



DEPARTMENT OF CHEMICAL ENGINEERING

Graduate Study and Research Leading to M.S. and Ph.D. Degrees

FACULTY AND AREAS OF SPECIALIZATION

- ROBERT E. BABCOCK** ● Water Resources, Fluid Mechanics, Thermodynamic Properties
- PHILIP E. BOCQUET** ● Electrokinetics, Thermodynamics
- EDGAR C. CLAUSEN** ● Conversion of Biomass into Chemicals and Energy
- JAMES R. COUPER** ● Process Design and Economics, Polymers
- JAMES L. GADDY** ● Biochemical Engineering, Process Optimization
- JERRY A. HAVENS** ● Irreversible Thermodynamics, Fire and Explosion Hazard Assessment
- CHARLES SPRINGER** ● Mass Transfer, Diffusional Processes
- CHARLES M. THATCHER** ● Mathematical Modeling, Computer Simulation
- LOUIS J. THIBODEAUX** ● Chemical Separations, Chemodynamics
- JIM L. TURPIN** ● Fluid Mechanics, Biomass Conversion, Process Design
- J. REED WELKER** ● Risk Analysis, Fire and Explosion Behavior and Control

FINANCIAL AID

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For Further Details Contact:

Dr. James L. Gaddy, Professor and Head
Department of Chemical Engineering
227 Engineering Building, University of Arkansas
Fayetteville, AR 72701

Brown University



Graduate Study in Chemical Engineering

Faculty

- Hassan Aref, Ph.D. (Cornell)
- Joseph M. Calo, Ph.D. (Princeton)
- Bruce Caswell, Ph.D. (Stanford)
- Joseph H. Clarke, Ph.D. (Polytechnic Institute of New York)
- Richard A. Dobbins, Ph.D. (Princeton)
- Sture K.F. Karlsson, Ph.D. (Johns Hopkins)
- Joseph D. Kestin, D.Sc. (University of London)
- Joseph T.C. Liu, Ph.D. (California Institute of Technology)
- Paul F. Maeder, Ph.D. (Brown)
- Edward A. Mason, Ph.D. (Massachusetts Institute of Technology)
- T.F. Morse, Ph.D. (Northwestern)
- Peter D. Richardson, Ph.D., D.Sc. Eng. (University of London)
- Merwin Sibulkin, A.E. (California Institute of Technology)
- Eric M. Suuberg, Sc.D. (Massachusetts Institute of Technology)

Research Topics in Chemical Engineering

Chemical kinetics, combustion, two phase flows, fluidized beds, separation processes, numerical simulation, vortex methods, turbulence, hydrodynamic stability, coal chemistry, coal gasification, heat and mass transfer, aerosol condensation, transport processes, irreversible thermodynamics, membranes, particulate deposition, physiological fluid mechanics, rheology.

A program of graduate study in Chemical Engineering leads toward the M.Sc. or Ph.D. Degree. Teaching and Research Assistantships as well as Industrial and University Fellowships are available.

For further information write:

Professor J. Calo, *Coordinator*
Chemical Engineering Program
Division of Engineering
Brown University
Providence, Rhode Island 02912

Biomedical Engineering / Chemical Engineering at Carnegie-Mellon University

Drug Transport
Membranes

Vascular Physiology
Pharmacokinetics

Chemotaxis
Cancer Research

Fermentation
Biomaterials

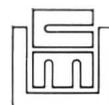
The Graduate Program offers M.S. and Ph.D. degrees in Biomedical Engineering / Chemical Engineering

M.S. in Biomedical Engineering / Chemical Engineering prepares engineering students for careers in industry and medical research.

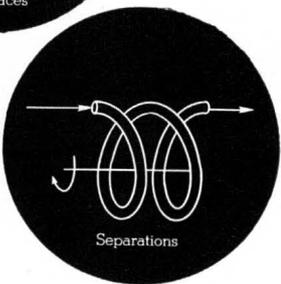
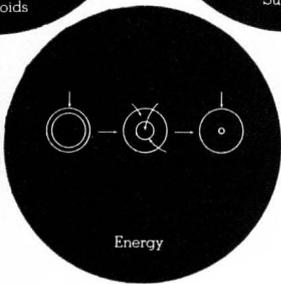
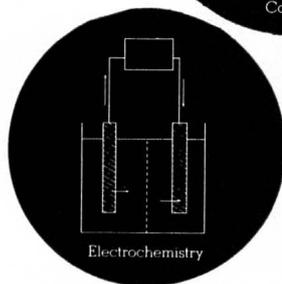
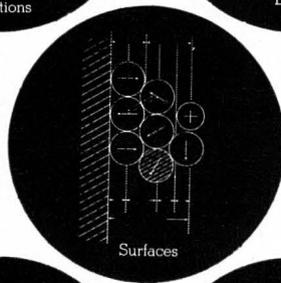
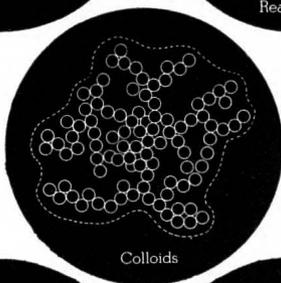
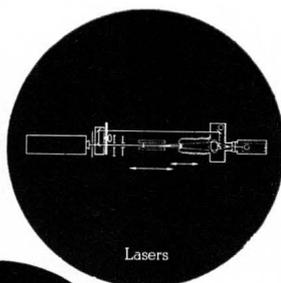
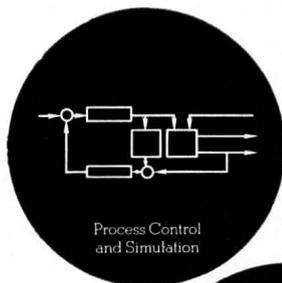
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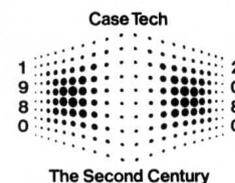
Chairman, Biomedical
Engineering Program
Carnegie-Mellon University
Pittsburgh, PA 15213



Carnegie-Mellon University



Select any of these eight distinct yet interrelated areas of ongoing research. For further information, contact:
Graduate Admissions Coordinator
Department of Chemical Engineering
Case Western Reserve University
Cleveland, Ohio 44106



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Professor Benjamin G. Levich
Institute of Applied Chemical Physics
City College—Steinman 202
New York, New York 10031



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Clemson University Clemson University is a state coeducational land-grant university offering 78 undergraduate fields of study and 58 areas of graduate study in its nine academic units which include the College of Engineering. Present on-campus enrollment totals about 11,000 students which includes about 1,500 graduate students. The campus, which comprises 600 acres and represents an investment of approximately \$195 million in permanent facilities, is located in the northwestern part of South Carolina on the shores of Lake Hartwell.

For Information For further information and a descriptive brochure, write D.D. Edie, Graduate Coordinator, Department of Chemical Engineering, Clemson University, Clemson, SC 29631.

THE CLEVELAND STATE UNIVERSITY

DOCTOR OF ENGINEERING

MASTER OF SCIENCE PROGRAM IN

CHEMICAL ENGINEERING



AREAS OF SPECIALIZATION

Transport Processes

Bioengineering

Simulation Processes

Porous Media

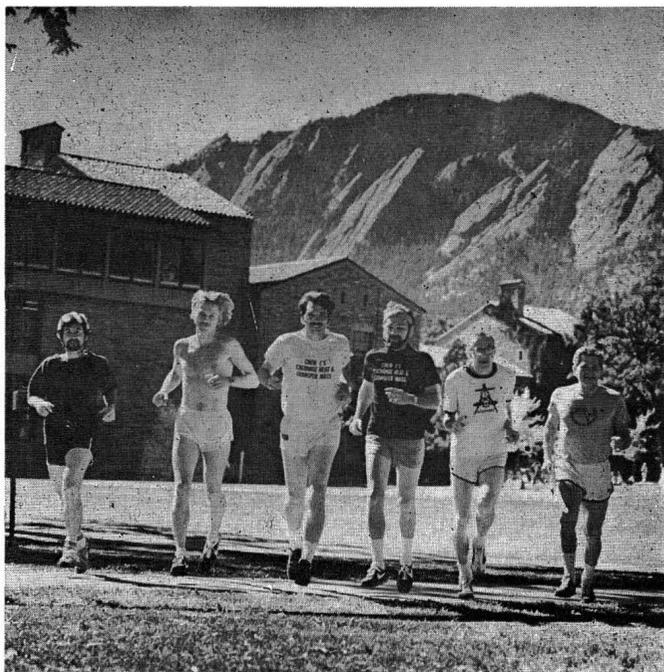
Reaction Engineering

Zeolites

The program may be designed as terminal or as preparation for further advance study leading to the doctorate. Financial assistance is available.

FOR FURTHER INFORMATION, PLEASE CONTACT:

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



l to r: Professors R. J. MacGregor, J. L. Falconer, W. F. Ramirez, W. B. Krantz, K. D. Timmerhaus, and M. S. Peters
not shown: Professors P. L. Barrick, D. E. Clough, R. I. Gamow, H. J. M. Hanley, R. C. Johnson, R. D. Noble, R. L. Sani, R. E. West, P. G. Glugla, L. Lauderback, and R. H. Davis

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WRITE TO:

*Professor Max S. Peters, Chairman'
Department of Chemical Engineering
Campus Box 424
University of Colorado
Boulder, CO 80309*

COLUMBIA UNIVERSITY
NEW YORK, NEW YORK 10027

Graduate Programs in Chemical Engineering,
Applied Chemistry and Bioengineering

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F. S. CASTELLANA	<i>Biomedical Engineering, Mass Transfer</i>
H. Y. CHEH	<i>Chemical Thermodynamics and Kinetics, Electrochemical Engineering</i>
C. J. DURNING	<i>Polymer Physical Chemistry</i>
H. P. GREGOR	<i>Polymer Science, Membrane Processes, Environmental Engineering</i>
C. C. GRYTE	<i>Polymer Science, Separation Processes</i>
E. F. LEONARD	<i>Biomedical Engineering, Transport Phenomena</i>
G. J. PROKOPAKIS	<i>Process Analysis, Simulation and Design</i>
J. L. SPENCER	<i>Applied Mathematics, Chemical Reactor Engineering</i>
U. STIMMING	<i>Electrochemistry</i>

For Further Information, Write:

Chairman, Graduate Committee
Department of Chemical Engineering and Applied Chemistry
Columbia University
New York, New York 10027

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**the
university
of
connecticut**

faculty

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M. B. CUTLIP
A. T. DiBENEDETTO
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R. A. WEISS

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Department of Chemical Engineering
The University of Connecticut
Storrs, Connecticut 06268

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S. M. Benner
E. D. Grossmann
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J. A. Tallmadge
J. R. Thygeson
X. E. Verykios
C. B. Weinberger

Research Areas

- Biochemical Engineering
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- Polymer Processing
- Process Control and Dynamics
- Rheology and Fluid Mechanics
- Systems Analysis and Optimization
- Thermodynamics and Process Energy Analysis

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Drexel University
Philadelphia, PA 19104

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R. C. CHAWLA , Ph.D., Wayne State	Air and Water Pollution Control, Reaction Kinetics
H. M. KATZ , Ph.D., Cincinnati	Environmental Engineering
F. G. KING , D.Sc., Stevens Institute	Biochemical Engineering, Process Control, Pharmacokinetics
M. G. RAO , Ph.D., Washington (Seattle)	Process Design, Ion Exchange Separations

For Information Write

Director of Graduate Studies
Department of Chemical Engineering
Howard University
Washington, DC 20059

CHEMICAL ENGINEERING M.S. and Ph.D. PROGRAMS

University of Idaho



FACULTY

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- D. C. DROWN** —Fluidized Bed Combustion and Pyrolysis, Process Design and Economic Evaluation
- L. L. EDWARDS** —Computer Aided Process Design, Systems Analysis, Pulp/Paper Engineering
- R. R. FURGASON** —Heat Transfer, Process Design and Economics
- D. S. HOFFMAN** —Applied Thermodynamics, Mass Transfer
- M. L. JACKSON** —Mass Transfer in Biological Systems, Particulate Control Technology
- R. A. KORUS** —Polymers, Biochemical Engineering
- J. Y. PARK** —Chemical Reaction Analysis and Catalysis
- J. J. SCHELDORF** —Heat Transfer, Thermodynamics
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A concentrated program of study in an informal atmosphere allows completion of a M.S. program in one calendar year. Graduate programs are also available for students having non-chemical degrees. The region has an invigorating climate with excellent outdoor recreation including fishing, hunting, skiing, hiking, boating, and camping. The university community provides access to a variety of cultural activities and events.

FOR FURTHER INFORMATION & APPLICATION WRITE:

Graduate Advisor
Chemical Engineering Department
University of Idaho
Moscow, Idaho 83843



THE JOHNS HOPKINS UNIVERSITY

FACULTY

- Stanley Corrsin, Ph.D.
Caltech
- Marc Donohue, Ph.D.
Berkeley
- Ini Ekpenyong, Sc.D.
M.I.T.
- Joseph Katz, Ph.D.
Chicago
- Robert Kelly, Ph.D.
North Carolina State
- Louis Monchick, Ph.D.
Boston
- Goeffrey Prentice, Ph.D.
Berkeley
- William Schwarz, Dr.Eng.
Johns Hopkins

Please contact:

Professor Robert Kelly
Department of Chemical Engineering
The Johns Hopkins University
Baltimore, Maryland 21218
301-338-8252

RESEARCH AREAS

Fluid Mechanics
Phase Equilibria
Biotechnology
Nucleation and Crystallization
Electrochemical Engineering
Rheology
Coal Conversion
Turbulence and Mixing
Mass and Heat Transfer
Process Modeling and Control
Reaction Engineering
Catalysis

M.S. AND Ph.D. PROGRAMS



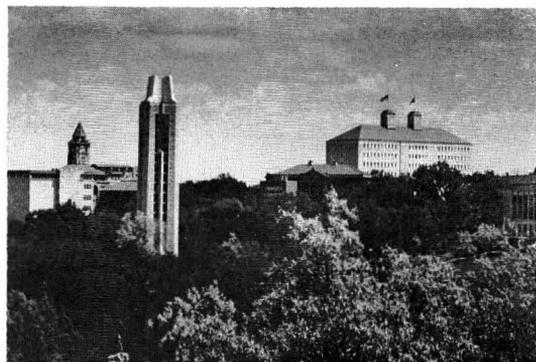
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For further information write:

Professor Russell Mesler, Graduate Adviser
Department of Chemical and Petroleum Engineering
4006 Learned Hall
The University of Kansas
Lawrence, Kansas 66045



Faculty and Areas of Specialization

Kenneth A. Bishop, Professor (Ph.D., Oklahoma); reservoir simulation, interactive computer graphics, optimization.

John C. Davis, Professor and chief of geology research section, Kansas Geological Survey (Ph.D., Wyoming); Probabilistic techniques for oil exploration, geologic computer mapping.

Kenneth J. Himmelstein, Adjunct Professor (Ph.D., Maryland); pharmacokinetics, mathematical modeling of biological processes, cell kinetics, diffusion and mass transfer.

Colin S. Howat, III, Assistant Professor (Ph.D., Kansas); applied equilibrium thermodynamics, process design.

Don W. Green, Professor and Co-director, Tertiary Oil Recovery Project, (Ph.D., Oklahoma); enhanced oil recovery, hydrological modeling.

James O. Maloney, Professor (Ph.D., Penn State); technology and society.

Russell B. Mesler, Professor (Ph.D., Michigan); nucleate and film boiling, bubble and drop phenomena.

Floyd W. Preston, Professor (Ph.D., Penn State); geologic pore structure.

Harold F. Rosson, Professor and Department Chairman (Ph.D., Rice); Production of alternate fuels from agricultural materials.

George W. Swift, Professor (Ph.D., Kansas); Thermodynamics of petroleum and petro

systems, natural gas reservoirs analysis, fractured well analysis, petro chemical plant design.

John E. Thiele, Associate Professor (Sc.D., MIT) polymers.

Shapour Vossoughi, Associate Professor (Ph.D., U. of Alberta); enhanced oil recovery thermal analysis, applied rheology and computer modeling.

Stanley M. Walas, Professor (Ph.D., Michigan); combined chemical and phase equilibrium.

G. Paul Willhite, Professor and Co-director Tertiary Oil Recovery Project, (Ph.D., Northwestern); enhanced oil recovery, transport processes in porous media, mathematical modeling.

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- Master of Engineering Science
- Doctor of Engineering

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- **K. Y. LI** (Ph.D., Mississippi State Univ.)
- **R. E. WALKER** (Ph.D., Iowa State Univ.)
- **C. L. YAWS** (Ph.D., Univ. of Houston)
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RESEARCH AREAS:

- Computer Simulation, Process Dynamics and Control
- Heterogeneous Catalysis, Reaction Engineering
- Fluidization and Mass Transfer
- Transport Properties, Mass Transfer, Gas-Liquid Reactions
- Rheology of Drilling Fluids, Computer-Aided Design
- Thermodynamic Properties, Cost Engineering, Photovoltaics

FOR FURTHER INFORMATION PLEASE WRITE:

Graduate Admissions Chairman
Department of Chemical Engineering
Lamar University
P. O. Box 10053
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Department of Chemical Engineering
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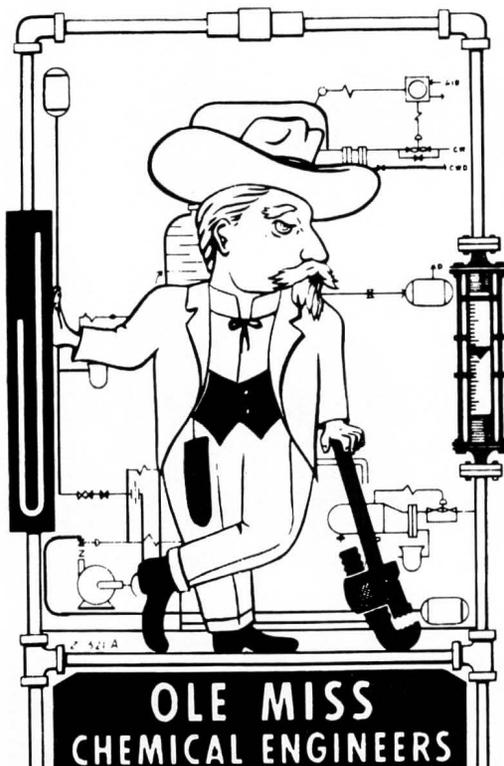
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Research Areas

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Biochemical Engineering and Biological Stabilization of Waste Streams

Biomedical Engineering

Catalysis

Energy Sources and Systems

Environmental Control Engineering

Heat and Mass Transport Influence by Fields

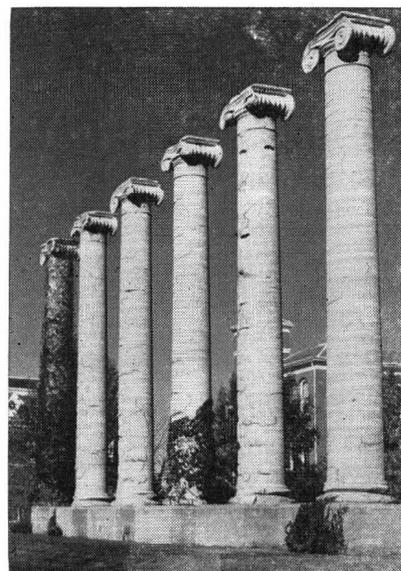
Newtonian and Non-Newtonian Fluid Mechanics

Process Control and Modelling of Processes

Single-Cell Protein Research

Thermodynamics and Transport Properties of Gases and Liquids

Transport in Biological Systems



WRITE: Dr. George W. Preckshot, Chairman, Department of Chemical Engineering, 1030 Engineering Bldg., University of Missouri, Columbia, MO 65211

UNIVERSITY OF NEBRASKA



CHEMICAL ENGINEERING



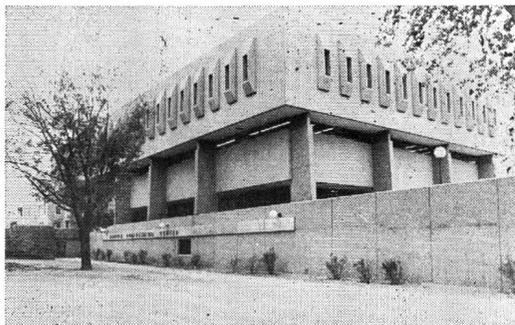
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Adsorption
Applied Mathematics
Biochemical & Biomedical
Catalysis, Kinetics, &
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Coal Conversion
Desalination &
Reverse Osmosis
Design and Economics
Fluidization
Mixing
Nuclear Engineering
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Tertiary Oil Recovery
Transport Phenomena
Wastewater Treatment

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Chemical Engineering at Notre Dame

RESEARCH AREAS

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Reaction Engineering
Phase Equilibria
Thermodynamics
Energy Conversion
Applied Mathematics
Process Dynamics and
Control
Modeling and Simulation
Transport Phenomena

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For further information, write to

Prof. A. Varma
Department of Chemical Engineering
University of Notre Dame
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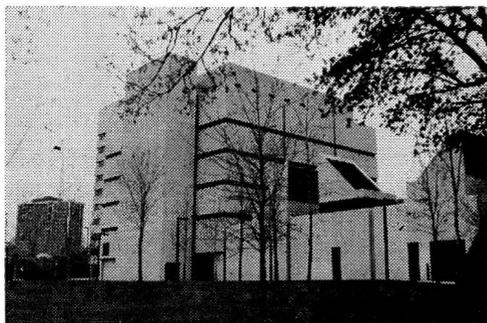


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| J. G. Knudsen | — Heat and Momentum Transfer, Two-Phase Flow |
| O. Levenspiel | — Reactor Design, Fluidization |
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Graduate applicants should write:

Graduate Coordinator, Chemical and Petroleum Engineering
School of Engineering
University of Pittsburgh
Pittsburgh, PA 15261

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Chemical Engineering
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Princeton, New Jersey 08544





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polymerization

reaction network analysis

statistical identification

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Food Engineering
Heat and Mass Transfer
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Mixing Research

Multiphase Flow
Phase Change Kinetics
Separation Process
Surface Phenomena

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Dr. Ronald S. Artigue
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Graduate Studies

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DEPARTMENT OF
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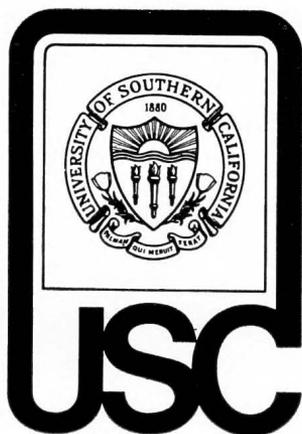


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W. J. DeCoursey	Absorption with chemical reaction, Mass transfer
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G. Hill	Petroleum Recovery, Numerical Modelling
D. Macdonald	Biochemical Engineering
J. F. Mathews	Heterogeneous Catalysis, Conversion of Natural Resources
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J. Postlethwaite	Corrosion Engineering
C. A. Shook	Transport Phenomena, Slurry Pipelines

For Information, Write

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Rheological properties of polymers and composites, adhesion, polymer processing

JOE D. GODDARD

(Ph.D., Ch.E., U.C. Berkeley, 1962)
Rheology and mechanics of non-Newtonian fluids and composite materials, transport processes

LYMAN L. HANDY

(Ph.D., Phys. Chem., U. of Wash., 1951)
Fluid flow through porous media and petroleum reservoir engineering

FRANK J. LOCKHART

(Ph.D., Ch.E., U. of Mich., 1943)
Distillation, air pollution, design of chemical plants

CORNELIUS J. PINGS

(Ph.D., Ch.E. Caltech, 1955)
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RONALD SALOVEY

(Ph.D., Phys. Chem., Harvard, 1958)
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KATHERINE S. SHING

(Ph.D. Cornell U., 1982)
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THEODORE T. TSOTSIS

(Ph.D., Ch.E., U. of Ill., Urbana, 1978)
Chemical reaction engineering, process dynamics and control

JAMES M. WHELAN

(Ph.D., Chem., U.C. Berkeley, 1952)
Thin Films III-V, heterogenous catalysis, sintering processes

YANIS C. YORTSOS

(Ph.D., Ch.E., Caltech, 1978)
Mathematical modelling and transport processes, flow in porous media and thermal oil recovery methods

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Department of Chemical Engineering
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Michel Boudart (Ph.D., 1950, Princeton)
Kinetics and Catalysis

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Polymer Science

Gerald G. Fuller (Ph.D., 1980, Cal Tech)
Microrheology

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K. D. Luks	– Thermodynamics, phase equilibria
F. S. Manning	– Industrial pollution control, enhanced oil recovery
W. C. Philoon	– Corrosion, process design
N. D. Sylvester	– Enhanced oil recovery, environmental protection, fluid mechanics, reaction engineering
R. E. Thompson	– Oil and gas processing, computer-aided process design

FURTHER INFORMATION If you would like additional information concerning specific research areas, facilities, and curriculum contact the Chairman of Chemical Engineering (Prof. Manning). Inquiries concerning admissions and financial support should be directed to the Dean of the Graduate School.

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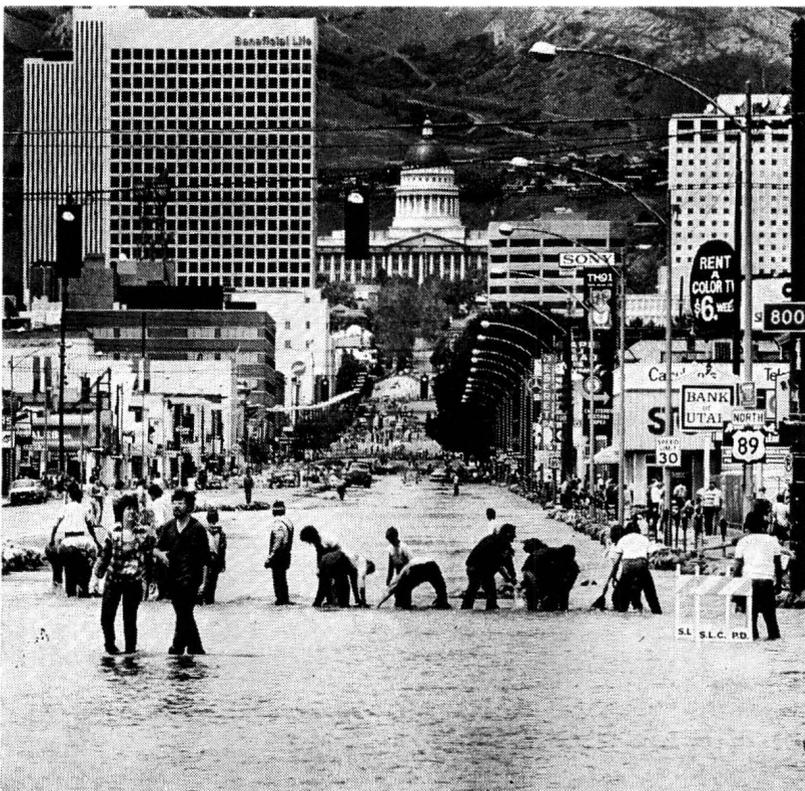
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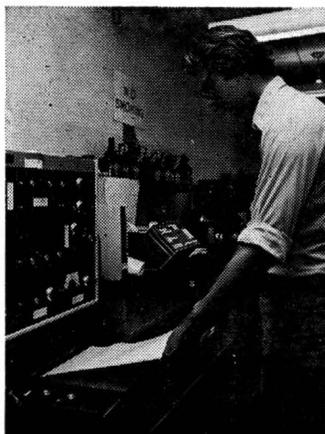
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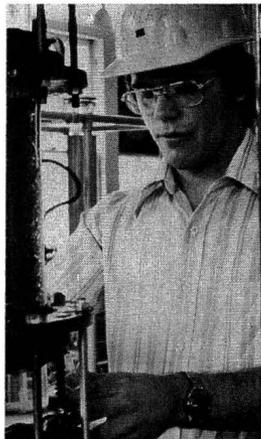
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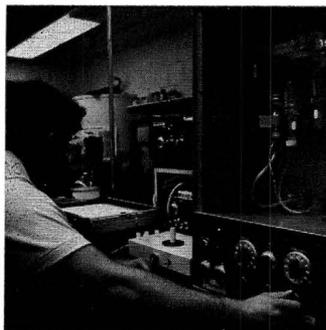
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