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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 yould like a copy of a previous Fall issue, please write CEE.

Ray Fahien, Editor, CEE
University of Florida

AUTHOR	TITLE
	Fall 1982
Hightower	"Oxidative Dehydrogenation Over Ferrite Catalysts"
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Russell	"Structure of the Chemical Processing Industries"
Vannice	"Heterogeneous Catalysis"
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Yen	"Coal Liquefaction Processes"
	Fall 1978
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Kabel	"Influential Papers in Chemical Reaction Engineering"
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Perlmutter	"Reactor Design From a Stability Viewpoint"
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Bailey & Ollis	"Biochemical Engr. Fundamentals"
DeKee	"Food Engineering"
Deshpande	"Distillation Dynamics & Control"
Johnson	"Fusion Reactor Technology"
Klinzing	"Environmental Courses"
Lemlich	"Ad Bubble Separation Methods"
Koutsky	"Intro. Polymer Science & Tech."
Reynolds	"The Engineer as Entrepeneur"
Rosner	"Energy, Mass and Momentum Transport"
	Fall 1975
Astarita	"Modern Thermodynamics"
Delgass	"Heterogeneous Catalysis"
Gruver	"Dynamical Syst. & Multivar. Control"
Liu	"Digital Computations for ChE's"
Manning	"Industrial Pollution Control"
McCoy	"Separation Process"
Walter	"Enzyme Catalysis"

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A Course in

NUMERICAL METHODS AND MODELING

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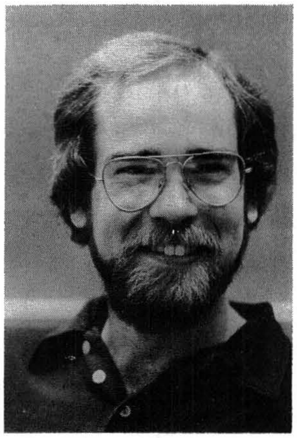

Mark Davis is an Assistant Professor of the Department of Chemical Engineering at Virginia Polytechnic Institute and State University since 1981. He earned his B.S., M.S. and Ph.D. (1981) from the University of Kentucky. He is currently working on research projects in zeolite catalysis, novel catalytic 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.

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**
   - **Runga-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**

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 compatable 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

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 reactor 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. Runga-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., Runga-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

$$A \underset{k_2}{\overset{k_1}{\rightleftharpoons}} B \xrightarrow{k_3} C, \; k_1 >> k_2 = k_3.$$

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) infinite 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.

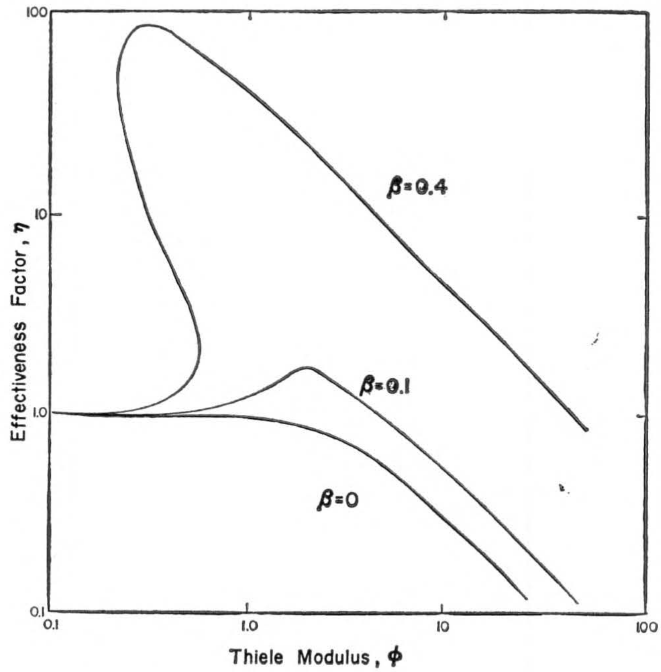

FIGURE 1. Effectiveness factor as a function of the Thiele modulus for a spherical catalyst pellet with first-order reaction.

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

The author wishes to thank Brandt Carter, Dan Pike, and Georg Viola for the solutions shown in Fig. 2, and to Young Park, J. C. Yang, and Nandu Madhekar for those illustrated in Fig. 1.

REFERENCES

1. Davis, M. E., *Numerical Methods and Modeling for Chemical Engineers*, John Wiley and Sons, in press.
2. Forsythe, G. E., M. A. Malcolm, and C. B. Moler, *Computer Methods for Mathematical Computations*, Prentice-Hall, Englewood Cliffs (1977).
3. Shampine, L. F., and H. A. Watts, "Global Error Estimation for Ordinary Differential Equations," ACM TOMS, 2, 172 (1976).
4. Shampine, L. F., and M. K. Gordon, *Computer Solution of Ordinary Differential Equations: The Initial Value Problem*, W. H. Freeman, San Francisco (1975).
5. Hindmarsh, A. C., "GEAR: Ordinary Differential Equation System Solver," Lawrence Livermore Laboratory Report UCID-30001 (1974).

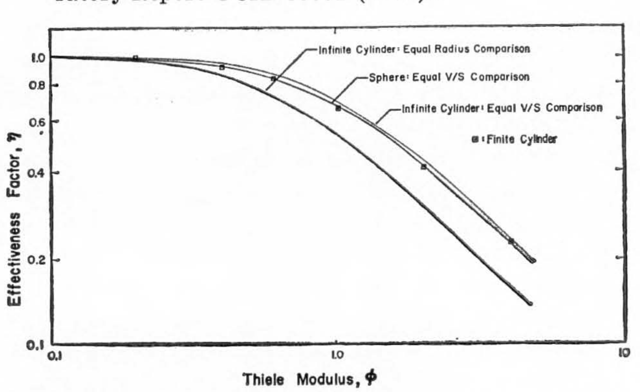

FIGURE 2. Effectiveness factor as a function of the Thiele modulus for isothermal pellets with first-order reaction.

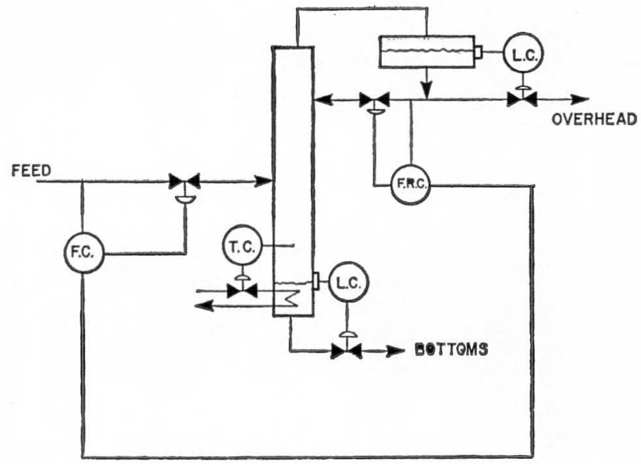

FIGURE 3. Feed-forward controlled distillation column. The column contains nine trays with the temperature control (T.C.) at tray 8, and the feed introduced on tray 6. F.C.: feed flow control, L.C.: liquid level control, F.R.C.: feed-forward control of the recycle from the measured feed flow rate.

6. Hindmarsh, A. C., "GEARB: Solution of Ordinary Differential Equations Having Banded Jacobians," Lawrence Livermore Laboratory Report UCID-30059 (1975).
7. Hindmarsh, A. C., "LSODE and LSODI, Two New Initial Value Ordinary Differential Equation Solvers," ACM SIGNUM Newsletter, December (1980).
8. Byrne, G. D., and A. C. Hindmarsh, "EPISODEB: An Experimental Package for the Integration of Systems of Ordinary Differential Equations with Banded Jacobians," Lawrence Livermore Laboratory Report UCID-30132 (1976).
9. Verwer, J. G., "Algorithm 553. MERK, An Explicit Time Integrator for Semidiscrete Parabolic Equations," ACM TOMS, *6*, 236 (1980).
10. Butcher, J. C., K. Burrage, and F. H. Chipman, "STRIDE Stable Runga-Kutta Integrator for Differential Equations," Report Series No. 150, Department of Mathematics, University of Auckland, New Zealand (1979).
11. Villadsen, J., and M. L. Michelsen, *Solution of Differential Equation Models by Polynomial Approximation*, Prentice-Hall, Englewood Cliffs (1978).
12. Skeel, R., and A. Kong, "Blended Linear Multistep Methods," ACM TOMS, *3*, 326 (1977).
13. Tendler, J. M., T. A. Bickard, and Z. Picel, "Algorighm 534. STINT: STiff INTegrator," ACM TOMS, *4*, 399 (1978).
14. Addison, C. A., "Implementing a Stiff Method Based Upon the Second Derivative Formulas," University of Toronto Department of Computer Science Technical Report No. 130/79 (1979).
15. International Mathematics and Statistics Libraries Inc., Sixth Floor—NBC Building, 7500 Bellaire Boulevard, Houston, Texas.
16. Weisz, P. B., and J. S. Hicks, "The Behavior of Porous Catalyst Particles in View of Internal Mass and Heat Diffusion Effects," Chem. Engng. Sci., *17*, 265 (1962).

A Course on

PLASMA PROCESSING IN INTEGRATED CIRCUIT FABRICATION

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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.

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 exchange, 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.

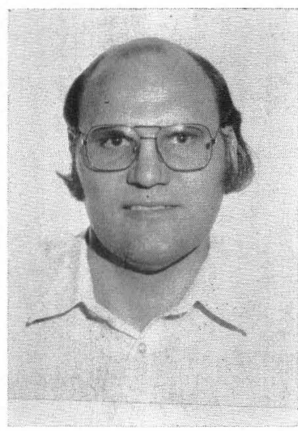
The goal of this course is to teach the fundamental science of plasma processing as well as to give a brief overview of the present state of industrial processes. This goal has a number of motivations. First, we perceive a general lack of understanding within the industrial community with regard to the 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.

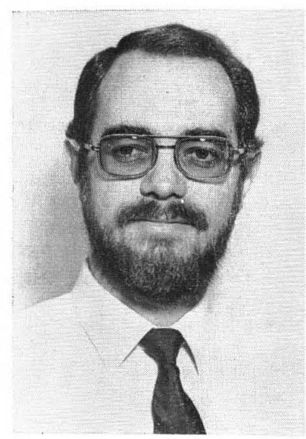
The present engineering state of the art is advancing extremely rapidly with the demands made by the microelectronics industry. We feel that by equipping the students with an understanding of the basics, they will be prepared to make the best use of the advancements. We also feel that an overview of 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 microelectronic 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

Gas Kinetics I: Collision cross-sections, energy transfer, ionization, excitation, relaxation

Gas Kinetics II: Completion of lectures

Electron Energy Distribution I: Plasma kinetic theory, transport phenomena

Plasma Chemistry: Plasma chemical reactions, reaction cross-sections, free radical reactions

DC Glow Discharges: Glow architecture, secondary emission, cathode and anode glow

RF Glow Discharges I: RF coupling, glow architecture, voltage distribution

RF Discharges II: Self-biasing, ion bombardment energies, electron energy distributions

Sputtering Kinetics: Sputtering yields, mechanisms, chemical enhancement

Optical Emission: Emission mechanisms, nomenclature, detectors

Laser Induced Fluorescence: Laser probes, mass spectroanalysis, quantification

Other Plasma Probes: Langmuir probes, mass spectrometer, microwaves

Sputter Deposition I: Sputtering physics, DC and RF sputtering, ion beams, magnetron

Sputter Deposition II: Etch rates, masks, profile control, ion beam vs. conventional, mask erosion, redeposition, angular dependence

Overview of Plasma Etching: definitions, wet vs. dry, uses, isotropic vs. anisotropic, selectivity

Etching Apparatus: Parallel plate, reactive ion etching, tunnel, reactive ion beam etching, costs, through-put, wet etch comparison

General Principles of Etching: Volatilization, additives, F and Cl etchants, flow, loading, example of a simple system (O_2 etching of organics)

Review of Si and SiO_2 etching

Aluminum Etching

Etching of Si_3N_4

Plasma Etch Control: Flowrate, power and bias, endpoint detection

Plasma Assisted Chemical Vapor Deposition: Overview, equipment considerations, commercial reactors

PACVD of Si_3N_4 and SiO_2

PACVD of Amorphous Si

PACVD of Poly- and Mono- crystalline Si and GaAs

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

REFERENCES

1. B. Chapman, *Glow Discharge Processes*, Wiley-Interscience (1980).
2. J. Hollahan and A. Bell, *Techniques and Applications of Plasma Chemistry*, Wiley-Interscience (1974).
3. J. Hirschfelder, C. Curtis, and R. Bird, *Molecular Theory of Gases and Liquids*, John Wiley and Sons (1954).
4. B. Cherrington, *Plasma Chemistry and Plasma Processing, 2*, 113 (1982).
5. W. Harshbarger, T. Porter, T. Miller, and P. Norton, *Applied Spectroscopy, 31*, 201 (1977).
   J. Greene, *Journal of Vacuum Science and Technology, 15*, 1718 (1978).
6. V. Donnelly, D. Flamm, and G. Collins, *Journal of Vacuum Science and Technology, 21*, 817 (1982).
7. J. Greene and S. Barnett, *Journal of Vacuum Science and Technology, 21*, 285 (1982).
   C. Horwitz, *Journal of Vacuum Science and Technology A, 1*, 60 1983.
8. M. Tsuda, S. Oikawa, D. Ohnogi and A. Suzuki, *Proceedings of the 6th International Conference on Microlithography* edited by P. Krammer, Delft University, Amsterdam (1980).

A Course in

ADVANCED TOPICS IN HEAT AND MASS TRANSFER

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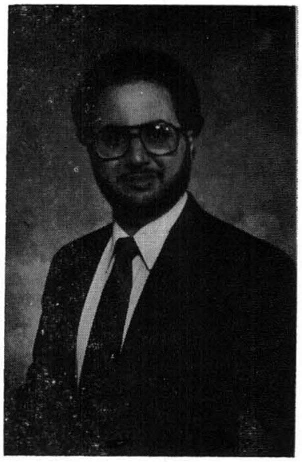

Joseph A. Shaeiwitz received his B.S. degree from the University of Delaware in 1974, and his M.S. and Ph.D. from Carnegie-Mellon University in 1976 and 1978, respectively. He has been on the faculty at the University of Illinois, Urbana, since 1978. Professor Shaeiwitz's research interests are in mass 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.

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 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 shortchanged. 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

1. Review (one week)
   A. Shell Balances[6]
      - Simple cases
      - Cases involving more complex math
      - Boundary condition or source term?
   B. Equations of Change [6]
      - Derivations for continuity, momentum and heat transfer
         - Differential cube
         - Divergence theorem
      - Different types of fluxes
      - A continuum entropy equation
      - Macroscopic balances [6, 7]
2. Diffusive Transport (three weeks) [9, 10, 15, 19, 21]
   A. Steady
      - Slabs and membranes
         - 1-dimensional
         - Multidimensional
   B. Unsteady
      - Solution methods
         - Combined variable
         - Laplace Transform
         - Fourier Transform
         - Separation of variables
         - Duhamel's Theorem
      - Physical considerations
         - When to use a solution method
         - Controlling resistances
         - Short vs. long time solutions
         - Intermediate regime
3. Simultaneous Heat and Mass Transfer (one week)
   A. Change of Phase Problems [9, 21]
   B. Fog Formation—An Interesting Example [31]
   C. Moving Boundary Problems in General [10, 12]
4. Convective Transport (three weeks)
   A. Closed Channels [15, 17, 29]
      - Graetz problem
         - Leveque solution
         - Sturm-Liouville solutions
         - Asymptotic behavior far from entrance
      - Analogy to heat conduction
   B. External Surfaces [15, 17, 18, 20, 26, 29]
      - Boundary layer theory
         - Ordering arguments
         - General solutions
         - Important limiting cases
         - Other approximate solution methods
      - Integral methods
   C. Unsteady Convective Transport
   D. Turbulent Transport
5. Interfacial Transport (one week)
   A. Resistances in Series
   B. Classical Theories
   C. Coupling between Navier-Stokes, Energy and Continuity Equations [4, 5, 30]
   D. Other Interface Models
      - Interface as a separate phase [4, 5]
      - Forced diffusion [8]
6. Mass Transfer with Chemical Reaction (one week)
   A. Heterogeneous Reaction
      - Resistances in series
      - Applications
   B. Homogeneous Reaction [2, 13]
      - Rapid reaction
      - Instantaneous reaction
      - Interface models
7. Theory of Diffusion and Other Transport Processes (three weeks)
   A. Diffusivity Measurement Techniques [11]
   B. Diffusion vs. Sedimentation
   C. Irreversible Thermodynamics [14, 16]
      - Entropy production
      - Coupled phenomena
   D. Reacting and Interacting Systems [11]
   E. Electrostatically Coupled Systems [11]
   F. Multicomponent Diffusion [11]
      - Tracer, intra-, self and mutual diffusion [1]
      - Solution of coupled equations
   G. Multicomponent Mass Transfer [11]
8. Carrier-Membranes (one week) [11]
   A. Physical Situation—an interesting example of multicomponent transport and mass transfer with chemical reaction
   B. Carrier Systems
      - Facilitated transport
      - Co-transport
      - Counter-transport
   C. Irreversible Thermodynamics Formulation
9. Particle Transport (one week)
   A. Failure of Continuum Theories—Need for Statistical Theories [3]
   B. Particle Adsorption—the intermolecular force boundary layer [23, 24]
   C. Particle Chromatography [24, 25, 28]

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 decrease 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.

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.

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 transport 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 alotted to interfacial transport involves changing the misconceptions about interfaces obtained by all students in their undergraduate mass transfer operations 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.

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.

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 μm 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 relevent 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. □

REFERENCES

1. Albright, J. G. and R. Mills, *J Phys Chem, 69,* 3120 (1965).
2. Astarita, G., "Mass Transfer with Chemical Reaction," Elsevier, New York, 1967.
3. Batchelor, G., *J. Fluid Mech., 52,* 245 (1972); *74,* 1 (1976).
4. Berg, J. C., "Interfacial Phenomena in Fluid Phase Separation Processes," in *CRC Recent Developments in Separation Science, 2,* 1 (1971).
5. Berg, J. C., *Can. Met. Quart., 2,* 121 (1982).
6. Bird, R. B., W. E. Stewart and E. N. Lightfoot, *Transport Phenomena,* Wiley, New York, 1960.
7. Bird, R. B., *Chem. Eng. Sci., 6,* 123 (1957).
8. Brenner, H. and L. G. Leal, *AIChE J, 24,* 246 (1978).
9. Carslaw, H. S. and J. C. Jaeger, "Conduction of Heat in Solids," (2nd ed.) Oxford, Oxford, England, 1959.
10. Crank, J., "The Mathematics of Diffusion," (2nd ed.) Oxford, Oxford, England, 1975.
11. Cussler, E. L., "Multicomponent Diffusion," Elsevier, New York, 1976.
12. Danckwerts, P. V., *Trans. Farad Soc., 46,* 701 (1950).
13. Danckwerts, P. V., "Gas-Liquid Reactions," McGraw-Hill, New York, 1970.
14. deGroot, S. R. and P. Mazur, "Non-Equilibrium Thermodynamics," Wiley, New York, 1962.
15. Eckert, E. R. G. and R. M. Drake, "Analysis of Heat and Mass Transfer," McGraw-Hill, New York, 1972.
16. Katchalsky, A. and P. F. Curran, "Non-Equilibrium Thermodynamics in Biophysics," Harvard Press, Cambridge, MA, 1965.
17. Kays, W. M. and M. E. Crawford, "Convective Heat Transfer," McGraw-Hill, New York, 1980.
18. Levich, V., "Physicochemical Hydrodynamics," Prentice-Hall, Englewood Cliffs, NJ, 1962.
19. McAdams, W. H., "Heat Transmission," (3rd ed.), McGraw-Hill, New York, 1954.
20. Newman, J. S., "The Fundamental Principles of Current Distribution and Mass Transport in Electrochemical Cells," in *Electroanalytical Chemistry: A Series of Advances* (A. J. Bard, ed), *6,* 187 (1973).
21. Osizik, M. N. "Heat Conduction," Wiley-Interscience, New York, 1980.
22. Perry, R. H. and C. H. Colton, "Chemical Engineers Handbook," (5th ed.) McGraw-Hill, New York, 1973.
23. Ruckenstein, E. and D. C. Prieve, *J. Chem. Soc. Faraday II, 69,* 1522 (1973).
24. Ruckenstein, E. and D. C. Prieve, *AIChE J, 22,* 276 (1976).
25. Ruckenstein, E., A. Marmur and W. N. Gill, *J. Coll. Int. Sci., 61,* 183 (1977).
26. Schlichting, H., "Boundary Layer Theory," (7th ed.) McGraw-Hill, New York, 1979.
27. Sherwood, T. K., R. E. Pigford and C. R. Wilke, "Mass Transfer," McGraw-Hill, New York, 1975.
28. Silebi, C. and A. J. McHugh, *AIChE J., 24,* 204 (1978).
29. Skelland, A. H. P., "Diffusional Mass Transfer," Wiley, New York, 1974.
30. Sternling, C. V. and L. E. Scriven, *AIChE J., 5,* 514 (1959).
31. Toor, H. L., *AIChE J., 17,* 5 (1971); *IEC Fund, 10,* 121 (1971).

A Course in

CHEMICAL REACTOR DESIGN

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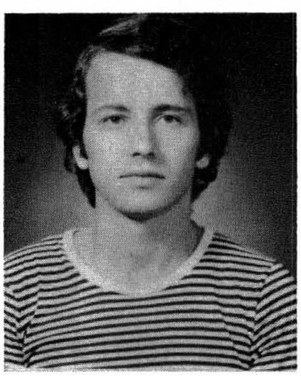
A FIFTEEN WEEK COURSE in chemical reactor design was prepared to meet the needs of graduate students in Purdue's School of Chemical Engineering. Since this is essentially the only graduate course on chemical reaction engineering in our school, a variety of topics was included. The course outline is given 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]



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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

TABLE 1
Course Outline

- 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
- 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
- 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
- Polymerization. Biochemical and Fermentation Kinetics
  - Polymerization mechanisms and kinetics
  - Microbial kinetics and dynamics
  - Growth of a single population
  - Growth of mixed populations
- 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
- Conservation Equations for Chemically Reacting Multicomponent Mixtures in Continuous Media
  - The continuity equations
  - The energy equation
  - The momentum equation
  - Equation for a retreating surface
- 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
  - Lumped resistance models
  - Uniqueness and multiplicity criteria
- 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
- Catalyst Deactivation
  - Types of catalyst deactivation
  - Kinetics of catalyst poisoning
  - Kinetics of catalyst deactivation by coking
  - Separability of catalytic deactivation kinetics
- Non-catalytic Reactions
  - Solid-fluid reactions
  - Gas-liquid reactions
- The Batch Reactor
  - The isothermal and non-isothermal batch reactor
  - Optimal operation policies and control strategies
- 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
- 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
- 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
- Nonideal Continuous Flow Reactors
  - Age-distribution functions
  - Application of age-distribution functions
  - Flow models
- 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
- 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
- Optimization of Chemical Reactors
  - Conventional and unconventional optimization
  - Globally optimal design.

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. □

REFERENCES

1. Froment, G. F., and K. B. Bischoff, "Chemical Reactor Analysis and Design", John Wiley and Sons, 1979.
2. Lapidus, L., and N. R. Amundson, "Chemical Reactor Theory, A Review", Prentice Hall, 1977.
3. Aris, R., "Introduction to the Analysis of Chemical Reactors", Prentice Hall, 1965.
4. Boudart, M., "Kinetics of Chemical Processes", Prentice Hall, 1968.
5. Stewart, W. E., W. H. Ray, and C. C. Conley, "Dynamics and Modelling of Reactive Systems", Academic Press, 1980.
6. Wei, J., and J. C. W. Kuo, I. E. C. Fund, *8*, 114 (1969), "A Lumping Analysis in Monomolecular Reaction Systems."
7. Aris, R., "The Mathematical Theory of Diffusion and Reaction in Permeable Catalysts, Vols. I and II, Clarendon Press, 1975.
8. Pismen, L. M., Chem. Eng. Sci. *35*, 1950 (1980), "Kinetic Instabilities in Man-Made and Natural Reactors".
9. Aris, R., I. E. Chem. *56*, 22 (1964), "Chemical Reactor Analysis".
10. Herskowitz, M., and J. M. Smith, A.I.Ch.E. J. *29*, 1 (1983), "Trickle-Bed Reactors: A Review".
11. Wilde, D. J., "Globally Optimal Design", Wiley-Interscience, 1978.

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 salutory 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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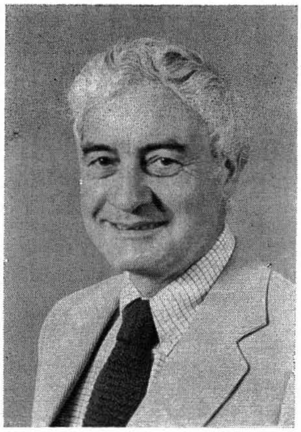
THERE APPEARS TO BE a difference in perception between teachers of chemical engineering and the industry which employs their students—a perceptual difference as to what constitutes a balanced course of instruction that best prepares the students for their industrial tasks. There is a point of view in 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 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.

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.

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.



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.

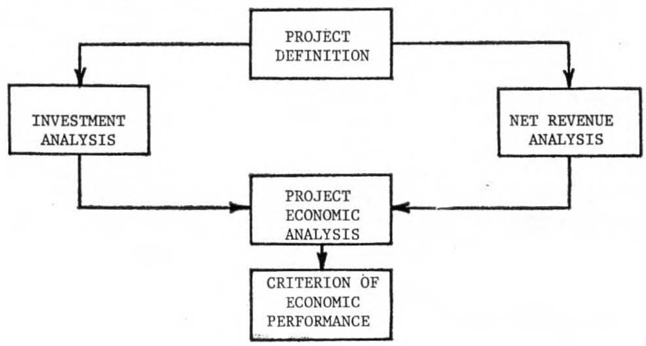


FIGURE 1

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.

Rèsumés. A first assignment in the course has been the assembly (or update) of the student's rèsumé. The instructor writes out an individual critique on each rèsumé 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 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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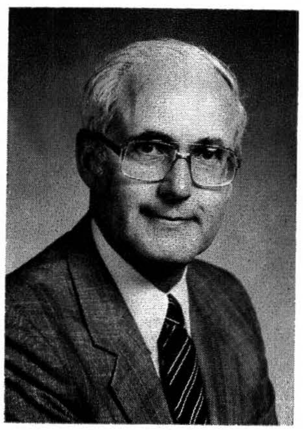
COLLOID AND SURFACE SCIENCE have been subjects of interest to scientists for many years. Within the last 20 years engineers have been paying more and more attention to this area of study. The more recent developments of the application of mathematical modelling and the gradual collection of numerical 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.



D. R. Woods is a graduate of Queen's University and the University of Wisconsin (Ph.D.). His teaching and research interests are in process analysis, and synthesis communication skills, cost estimation, separations, surface phenomena and developing problem solving skills. He is the author of "Financial Decision-Making in the Process Industry." He received the Ontario Confederation of University Faculty Association award for Outstanding Contribution to University Teaching.

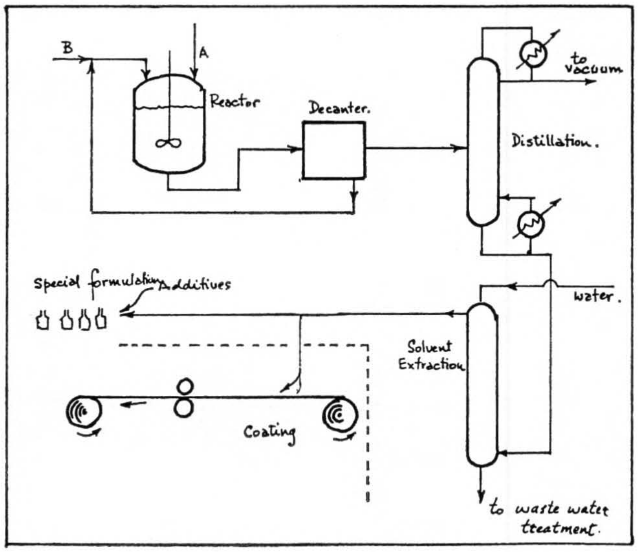


FIGURE 1. An imaginary process.

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 aniosotropy 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 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

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

TABLE 1
Analogous Properties in Bulk and Surface Phases

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

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

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

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:

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

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

$$\gamma_{I-II} \cos\theta_{123} = \gamma_{I-III} - \gamma_{II-III} - \pi_{III,2} - \pi_{III,1} - \pi_{I-III,2} + \pi_{II-III,1}$$

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 $mN{\cdot}m^{-1}$), 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 Capillary number defined as

$$\mathrm{Ca} = \frac{v_{CL}\,\mu_{II}}{\gamma_{I-II}}$$

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 dropwise 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 accomodating 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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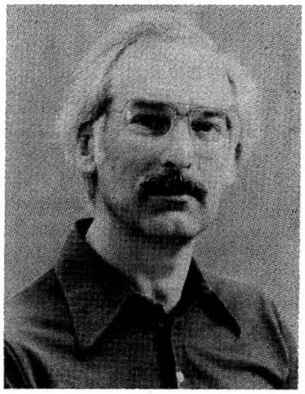
UNDERGRADUATE STUDENTS HAVE an opportunity for exposure to research through a number of methods utilized by many departments. Seniors often attend their department's graduate research seminar, which brings visitors to campus from other academic and industrial research laboratories. Independent study 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 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.



Stanley Middleman is Professor of Chemical Engineering at the University of California, San Diego. His undergraduate and doctoral degrees are from The Johns Hopkins University. He has authored three books: **The Flow of High Polymer, Transport Phenomena in the Cardiovascular Systems**, and **Fundamentals of Polymer Processing.** In addition to his responsibility for directing the establishment of the chemical engineering program at UCSD, he carries on an active research program in the field of fluid dynamics.

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.

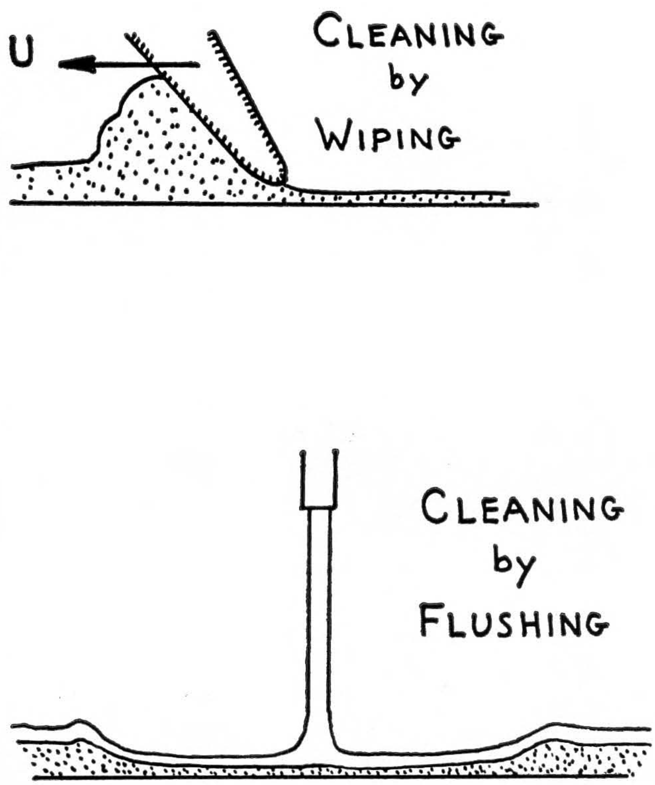


FIGURE 1. Liquid film may be removed from a surface by wiping, or flushing.

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

- **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 reproduceably 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-

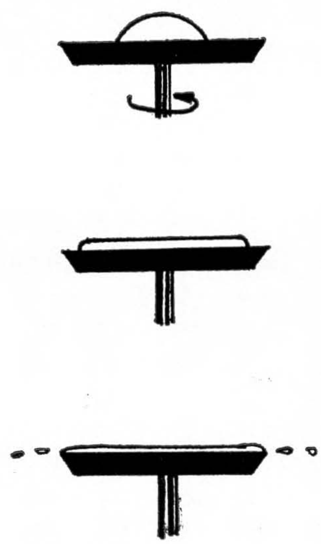


FIGURE 3. A thin liquid film may be spread on a surface by spinning.

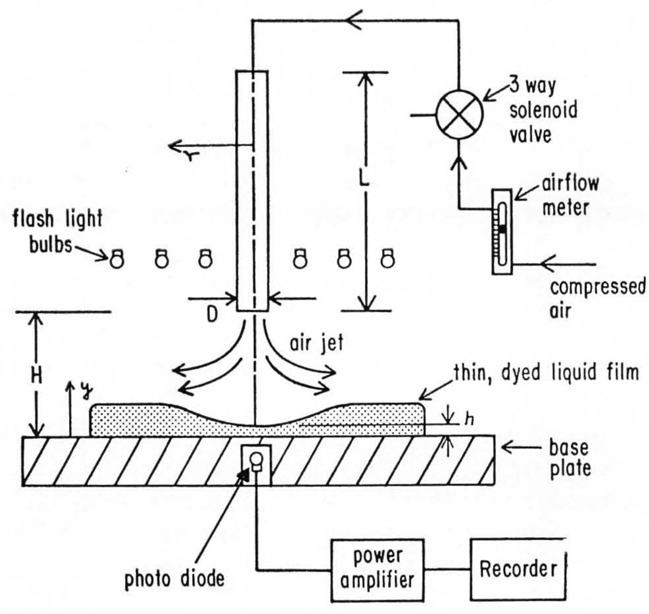


FIGURE 4. Schematic of apparatus for study of removal of a liquid film by an air jet.

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 provides 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

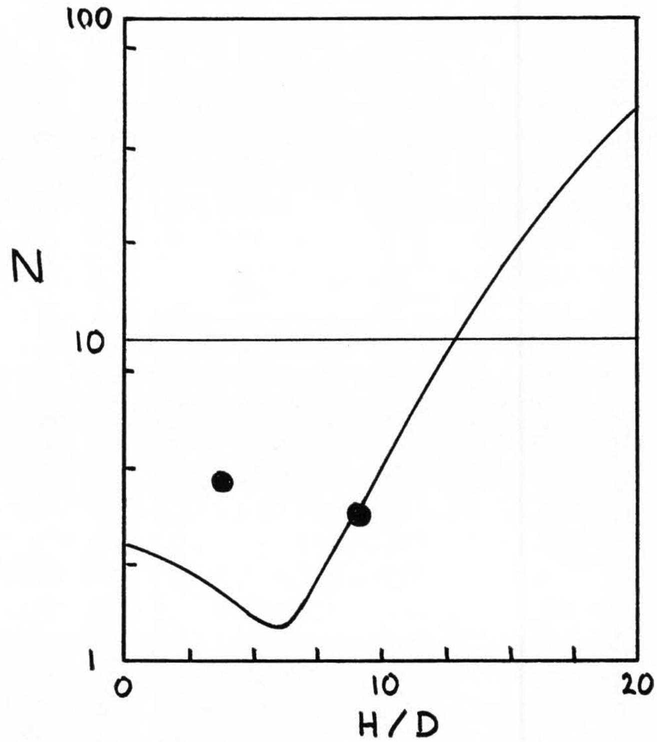


FIGURE 5. Data in support of a very simple model of film removal.

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

$$N = \rho\, u_0^2 h_0^2 t_{1/2}/\mu D^2 \tag{1}$$

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

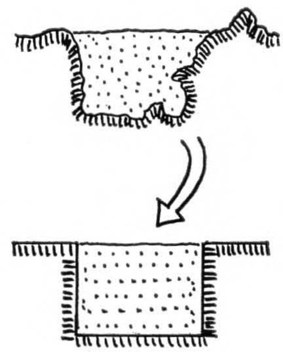


FIGURE 6. Idealization of a roughness element by a rectangular cavity.

- **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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Research on

COMBUSTION

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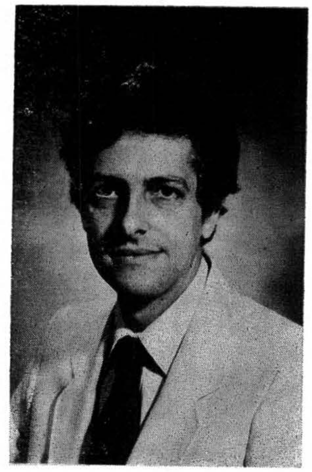


Mohamed A. Serageldin received his B.Sc. and M.Sc. in Chemical Engineering from Cairo University and his Ph.D. from Imperial College —London University.

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 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 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.

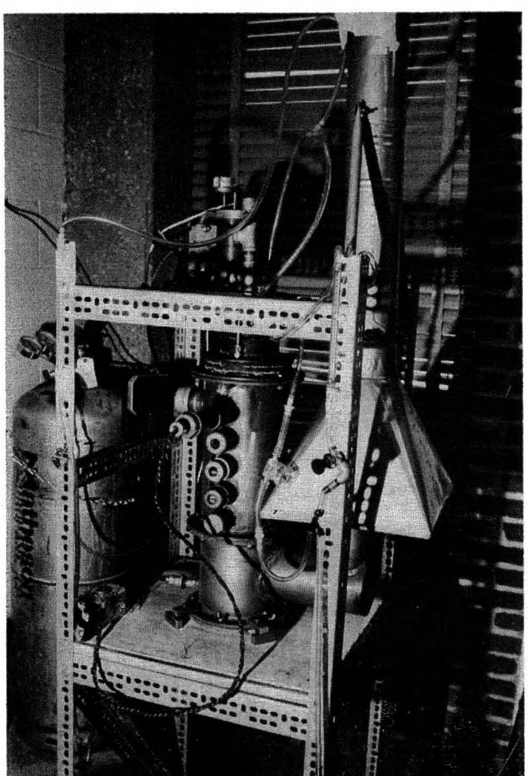


FIGURE 1. Coal combustor.

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).

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 $CO \rightarrow CO_2$ 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 distinguished between combustion of small, and combustion (and gasification) of large, coal particles. □

REFERENCES

1. Campbell, J., J. Scholl, F. Hibbler, S. Bagley, D. Leddy, D. Abata, and J. Johnson. The Effect of Fuel Injection Rate and Timing on the Physical, Chemical, and Biological Character of Particle Emissions from a Direct Injection Diesel. SAE Paper No. 810996, Transactions 1981.
2. Funkenbusch, E. F., D. Leddy, and J. H. Johnson, "The Characterization of the Soluble Organic Fraction of Diesel Particulate Matter," SAE/PT-79/17.
3. Miller, P. R., J. Scholl, S. Bagley, D. Leddy, and J. Johnson. The Effects of a Porous Ceramic Particulate Trap on the Physical, Chemical, and Biological Character of Diesel Particulate Emissions. SAE Paper No. 830475, 1983.
4. Ames, B. N., J. McCann, and E. Yamasaki. Methods for Detecting Carcinogens and Mutagens with the *Salmonella* Mammaliam-microsome Mutagenicity Test. Mutation Research 31: 347-364, 1975.
5. Belser, W. L., Jr., S. D. Shaffer, R. D. Bliss, P. M. Hynds, L. Yamamoto, J. N. Pitts, Jr., and J. A. Winer. Quantification of the Ames *Salmonella*/ Mammaliam-microsome Mutagenicity test. Environmental Mutagenesis 3: 123-139, 1981.
6. Bagley, S. T., Private Communication—1983.
7. Van Krevelin, D. W., "Development of Coal Research —a review"; Fuel 61, 786-90, 1982.
8. Special Issue of the papers presented at the International Symposium, "Fundamentals of Catalytic Coal and Carbon Gasification, held at Amsterdam. The Netherlands, 27-29 September 1982, Fuel 62 (2), 1983.
9. Elliot, M. A. (Editor): "Chemistry of Coal Utilization Second Supplementary Volume"; John Wiley and Sons, 1981.
10. Oschell, F. J. and E. J. Boccuzzi, Improved Coal Combustion Through Chemical Treatment. Combustion, 52, 32-5, 1980.
11. Serageldin, M. A., "Effect of Calcium Chloride on Coal Decomposition", Report presented to the Dow Chemical Company, 1983.
12. Serageldin, M. A., "An Examination of the Effects of Calcium Chloride on Corrosion of Mild-Steel by Scanning Electron Microscopy and X-ray Diffraction —Report presented to the Dow Chemical Company—1983.
13. Serageldin, M. A. and W. P. Pan, "Coal: Analysis Using Thermogravimetry", Presented at 185th National ACS Meeting, Seattle, Washington.
14. Reid, W. T., "Basic Problems in the Formation of Sulfate in Boiler Furnaces", Journal of Engineering for Power, Trans. ASME, Series A, Vol. 89, No. 2, 283-87, 1967.
15. Horton, M. D., F. P. Goodson, and L. D. Smoot, Characteristics of Flat, Laminar Coal-Dust Flames. Combust. Flame, 28, 187-195, 1977.
16. Serageldin, M. A. and W. P. Pan, "Coal Conversion: Effects of Heating Rate and Furnace Atmosphere," Proceedings of the 32nd Canadian Chemical Engineering Conference, Vancouver, British Columbia, October 3-6, 1982, Vol 1, pp. 442-51.
17. Flyn, J. H. and L. A. Wall, "General Treatment of Thermogravimetry of Polymers", J. Res. Nat. Bur. Stand. 50A, 487-523, 1966.
18. Serageldin, M. A. and W. P. Pan, "Coal: Kinetic Analysis of Thermogravimetric Data", to be published in Thermochimica Acta.
19. Semenov, N. N. "Some Problems in Chemical Kinetics and Reactivity"; Princeton University Press, 1958, Vol 1, 1-33.
20. Van Krevelin, D. W., "Coal"; Elsevier Publishing Co., N.Y., 1961.
21. O'Gorman, J. V., P. L. Walker, Jr., "Thermal Behavior of Mineral Fractions Separated from Selected American Coals", Fuel, 52, 71, 1973.

ChE book reviews

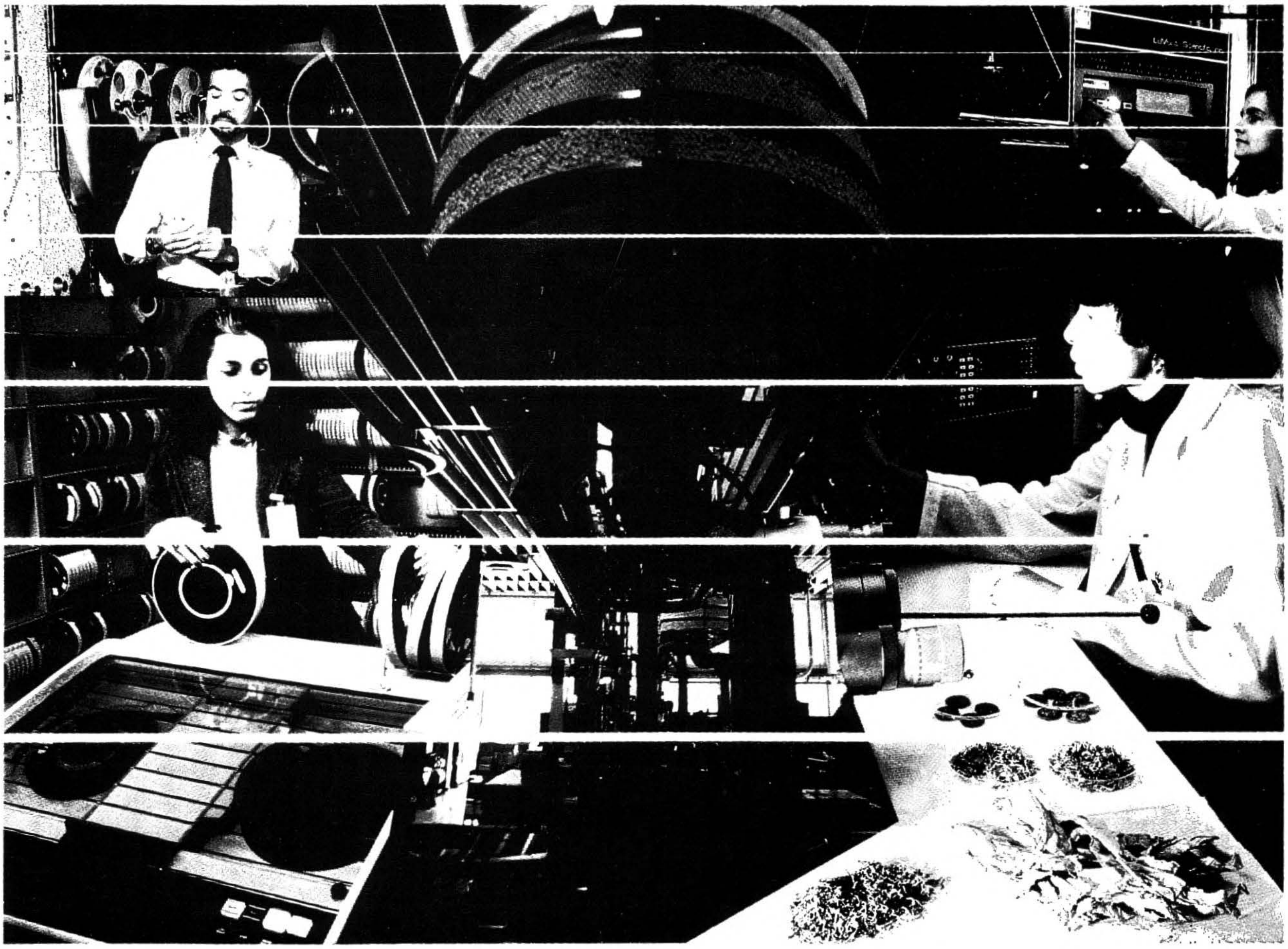
CHEMICAL REACTOR ANALYSIS AND DESIGN

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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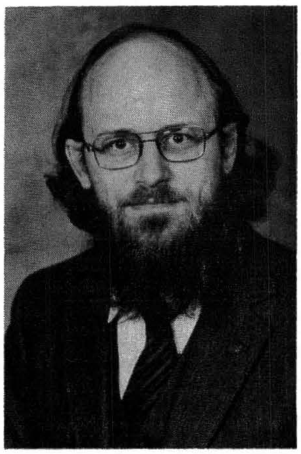
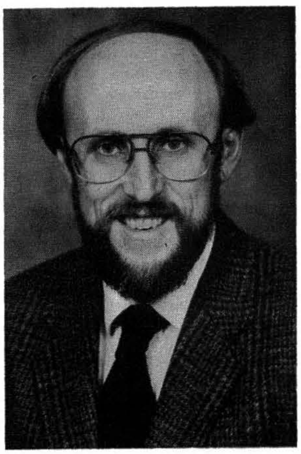
THE GRADUATE STUDENT'S GUIDE TO ACADEMIC JOB HUNTING

PHILLIP C. WANKAT AND
FRANK S. OREOVICZ
Purdue University
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 provides a guide for the steps and we will refer to it throughout the paper.





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)**

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

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 . . .

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

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.

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

WILLIAM J. THOMSON
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Pullman, WA 99164

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University of Idaho
Moscow, ID 83843

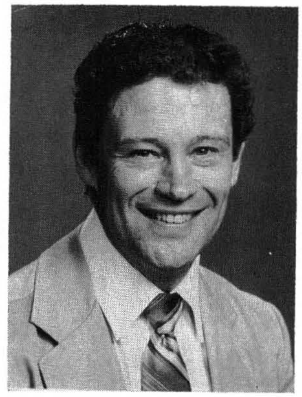
OUR DEPARTMENTS OF chemical engineering at Washington State University (WSU) and the University of Idaho (UI) have been successfully coordinating their graduate offerings for the past two years. The universities are just eight miles apart and travel time from classroom to classroom is under thirty minutes. 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.

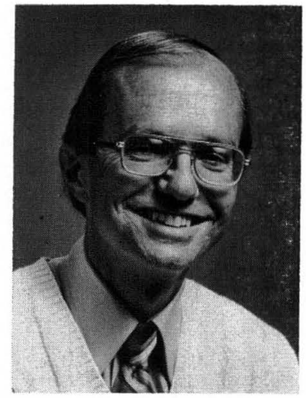
Historically, most of our entering graduate students pursue the Master of Science degree, with far fewer numbers opting and being accepted for doctorate work. To meet the needs of the master's student, a basic core of graduate level courses must be offered every year. This requirement left little room 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 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.





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)**

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

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

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.

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 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

*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.

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) 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.

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.

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, sparkling 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 curtailing 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 textbooks, 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.

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.

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 possibly. 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 publshing 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. Guggenhiem 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. □

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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.

REFERENCES

1. J. O. Hirschfelder, C. F. Curtiss, and R. B. Bird, "Molecular Theory of Gases and Liquids", Wiley, New York (1954); R. B. Bird, W. E. Stewart, and E. N. Lightfoot, "Transport Phenomena", Wiley, New York (1960); R. B. Bird and W. Z. Shetter, "Een Goed Begin", Martinus-Nijhoff, The Hague (1963); E. E. Daub, R. B. Bird, and N. Inoue, "Comprehending Technical Japanese", Univ. of Wisc. and Univ. of Tokyo Presses (1975); "Dynamics of Polymeric Liquids", Vol. 1 by R. B. Bird, R. C. Armstrong, and O. Hassager and Vol. 2 by R. B. Bird, O. Hassager, R. C. Armstrong, and C. F. Curtiss, Wiley, New York (1977).
2. T. H. Chilton, in "The First One Hundred and Fifty Years", John Wiley and Sons, Inc., New York (1957).
3. O. A. Hougen, "Seven Decades of Chemical Engineering", Chemical Engineering Progress, Jan. 1977, pp. 89-104.
4. W. F. Furter (Ed.), "History of Chemical Engineering", Adv. in Chem. Series, No. 190, Amer. Chem. Soc., Washington, D.C. (1980); W. F. Furter (Ed.), "A Century of Chemical Engineering", Plenum Publ. Co., New York (1982).
5. W. H. Walker, W. K. Lewis, and W. H. Adams, "Principles of Chemical Engineering", McGraw-Hill, New York (1923).
6. O. A. Hougen, K. M. Watson, and R. A. Ragatz, "Material and Energy Balances", Wiley, New York (1954); O. A. Hougen, K. M. Watson, and R. A. Ragatz, "Thermodynamics", Wiley, New York (1959); O. A. Hougen and K. M. Watson, "Kinetics and Catalysis", Wiley, New York (1947).
7. F. Weinhold, "Metric Geometry of Thermodynamics", *J. Chem. Phys.*, *63*, 2479-2501 (1975).
8. W. R. Marshall and R. L. Pigford, "The Application of Differential Equations to Chemical Engineering Problems", U. of Delaware Press, Newark, Del. (1947).
9. Limerick by Berton Braley, on p. 96 of "Out on a Limerick", by Benett Cerf, Pocket Books, Inc., New York (1962).
10. J. R. A. Pearson, "Mechanical Principles of Polymer Melt Processing", Pergamon, New York (1966), p. 1.
11. S. E. Martin, "Essential Japanese", Tuttle, Rutland, Vt. (1956).
12. A. A. P. Faculty Service, "An Author's Guide to Academic Publishing", College Div., Assoc. of Amer. Publishers, 1 Park Ave., New York, New York, 10016.
13. M. H. Bruno, "Status of Printing in the U.S.A.—1981", New England Printer & Publisher, July 1981, pp. 27-49.
14. P. Seybold, "An Introduction to Word Processing for Wiley Authors", John Wiley and Sons, New York (1982).
15. J. S. Allen, "The Importance of Style in Art and Life", Wall Street Journal, Nov. 26, 1982.

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,

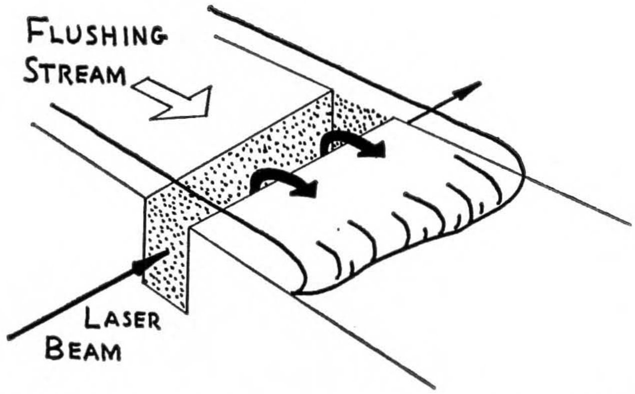

FIGURE 7. Experiment for study of removal of fluid from a cavity by an external stream.

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

This research program has been supported by the National Institute of Occupational Safety and Health (5R01OH01004) and by the Army Research Office (DAAG29-80-K0058).

REFERENCES

1. Greener, J., and S. Middleman, "Theoretical and Experimental Studies of the Fluid Dynamics of a Two-Roll Coater," *Ind. Eng. Chem. Fundamentals, 18,* 35 (1979).
2. Bauman, T., T. Sullivan, and S. Middleman, "Ribbing Instabilities in Coating Flows: Effect of Polymer Additives," *Chem. Eng. Commun., 14,* 35 (1982).
3. Oliver, J. F., and S. G. Mason, "Microspreading Studies on Rough Surfaces by SEM," *J. Coll. Int. Sci., 60,* 480 (1977).
4. Huh, C., and L. E. Scriven, "Hydrodynamic Model of Steady Movement of a Solid/Liquid/Fluid Contact Line," *ibid., 35,* 85 (1971).
5. Neogi, P., and C. A. Miller, "Spreading Kinetics of a Drop on a Rough Surface," *ibid., 92,* 338 (1983).
6. Giralt, F., C-J. Chia, and O. Trass, "Characterization of the Impingement Region in an Axisymmetric Turbulent Jet," *Ind. Eng. Chem. Fundamentals, 16,* 21 (1977).
7. Chilukuri, R., and S. Middleman, "Circulation, Diffusion, and Reaction within a Liquid Trapped in a Cavity," *Chem. Eng. Commun., 22,* 127 (1983).

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 applications, 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 compatable 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 in 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 atmosphere 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 CO_2 requires that tabulated CO_2 free energy must be corrected for the work that may, in theory but not in practice, be obtained by expanding CO_2 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°C) and the fog lifts (p_{H_2O} = .03 atm).

Sincerely,
Martin V. Sussman
Tufts University

[1] Sussman, M. V., "Availability (Exergy) Analysis," Mulliken House, 1361 Mass. Av., Lex, MA (1980)
[2] Szargut, J., *Freiberger Forschungshefte*, Nr. B6B, S. 81/103 (1962)
[3] Baehr, H. D., and E. F. Schmidt, *Brennstoff-Warme-Kraft*, Bd. 15, Nr. 8, 5375/81 (1963)
[4] Gaggioli, R. and P. J. Petit, *Chem. Tech.*, Z, 495-506 (1977)
[5] Ahrendts, J., Veriens Deutscher Ingenieure-Forschangsheft 579 (1977)

ChE books received

"Physical Cleaning of Coal: Present and Developing Methods," edited by Y. A. Liu; Marcel Dekker, Inc., New York; 552 pages, $75.00 (1982)

"The Oxide Handbook," Second Edition, edited by G. V. Samsonov; Plenum Publishing Corp., New York; 463 pages, $75.00 (1982)

"Los Alamos Shock Wave Profile Data," Charles Morris; Univ. of California Press, Berkeley, CA 94720; 488 pages, $35.00 (1982)

"Microemulsions," edited by I. D. Robb; Plenum Publishing Corp., New York 10013; 259 pages, $35.00 (1982)

"Plastics Polymer Science and Technology," edited by Mahendra D. Baijal; John Wiley & Sons, Inc., Somerset, NJ 08873; 945 pages, $150.00 (1982)

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

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Ph.D. Oregon State University, 1973
Transpiration Cooling, Heat Transfer in Biological Systems, Blood Processing

JOSEPH F. GROSS, Professor
Ph.D., Purdue University, 1956
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

THOMAS W. PETERSON, Assoc. Professor
Ph.D., California Institute of Technology, 1977
Atmospheric Modeling of Aerosol Pollutants, Long-Range Pollutant Transport, Particulate Growth Kinetics, Combustion Aerosols

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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

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

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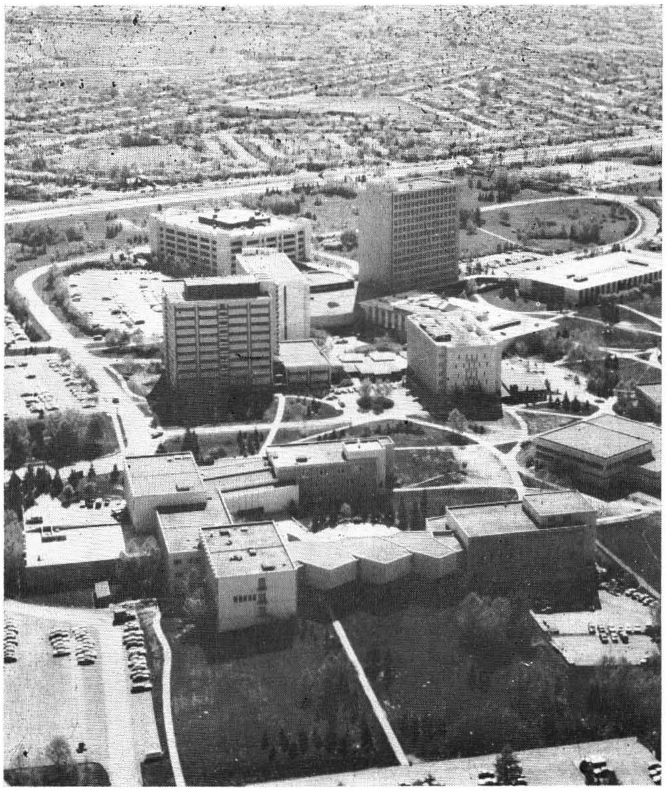

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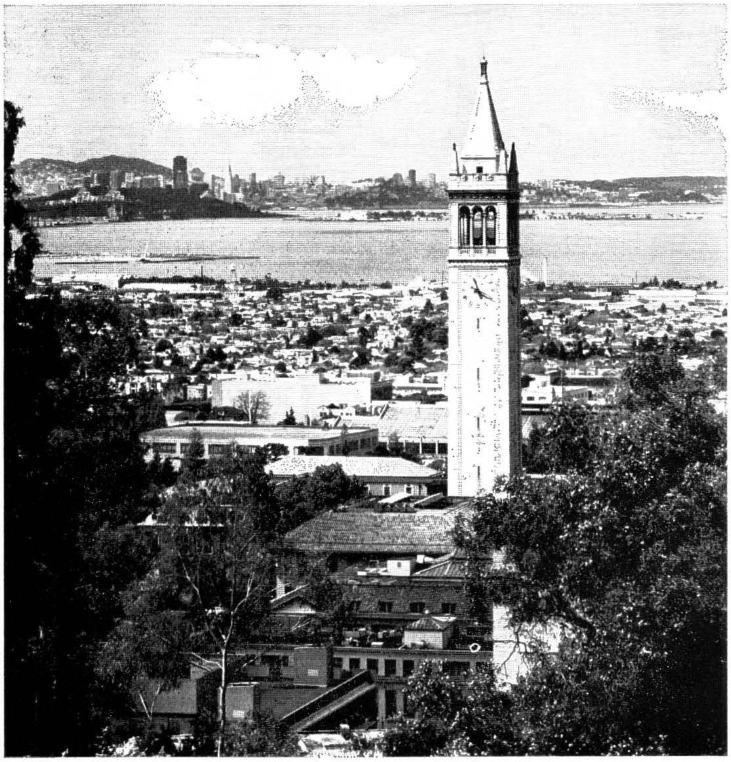

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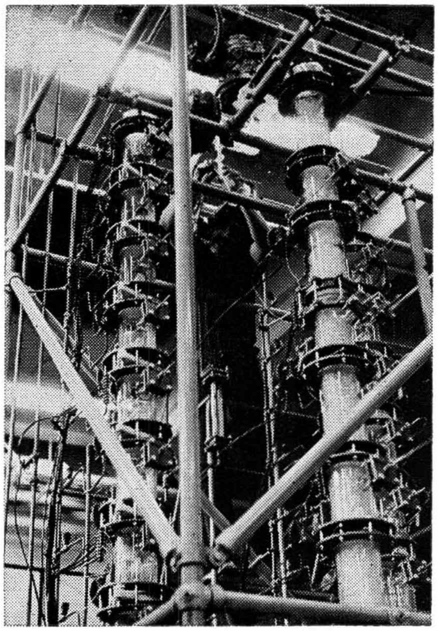

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ANGELES

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.

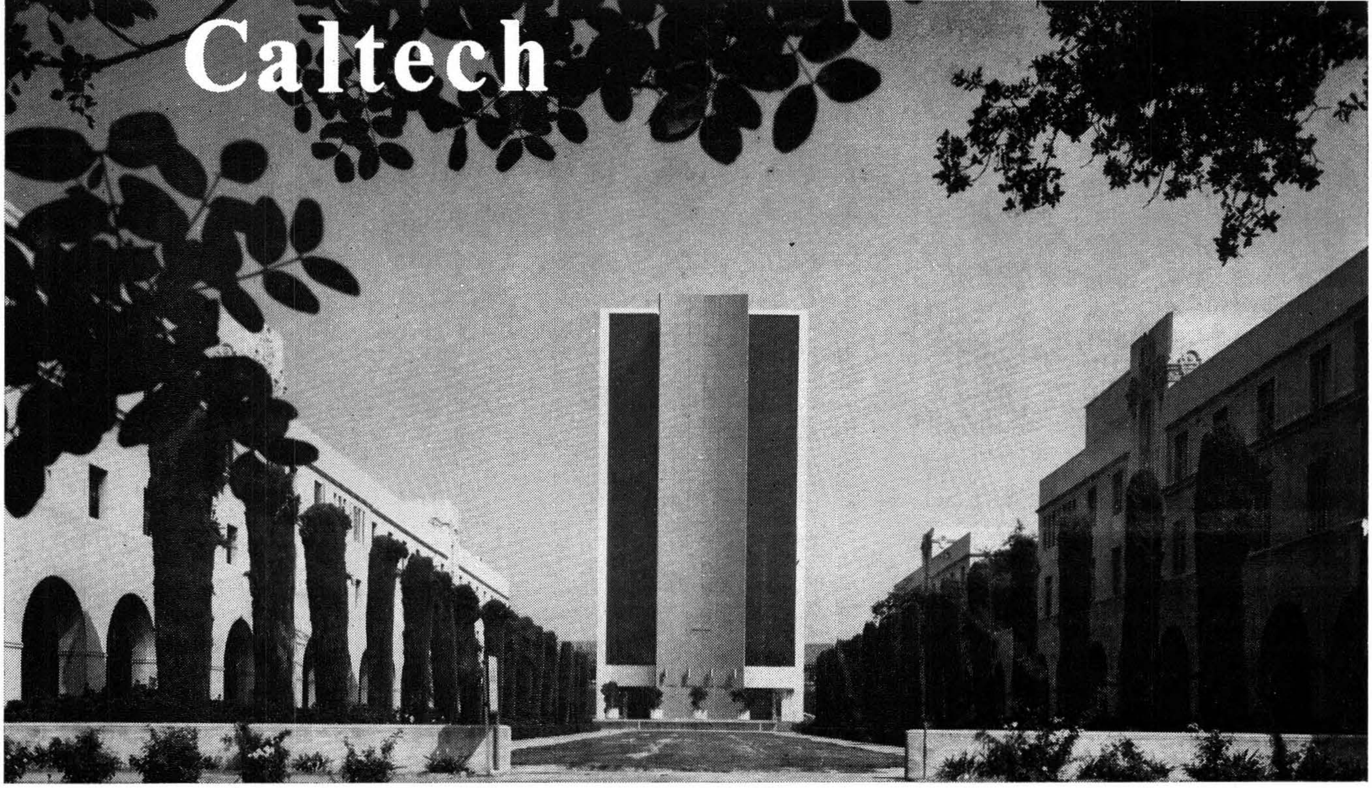
THE UNIVERSITY

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 tchnological 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

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.

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

The
UNIVERSITY OF CINCINNATI

GRADUATE STUDY in Chemical Engineering M.S. and Ph.D. Degrees

FACULTY

Stanley Cosgrove
Robert Delcamp
Joel Fried
Rakesh Govind
David Greenberg
Daniel Hershey
Sun-Tak Hwang
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

Computer-aided design. Modeling and simulation of coal gasifiers, activated carbon columns, process unit operations. Prediction of reaction by-products.

POLYMERS

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

AIR POLLUTION

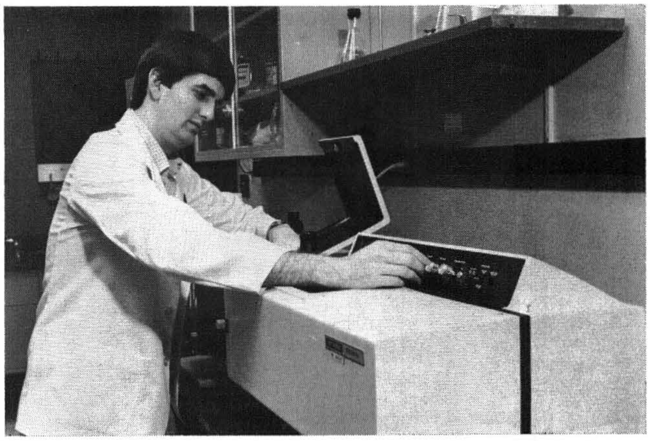
Modeling and design of gas cleaning devices and systems.

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.

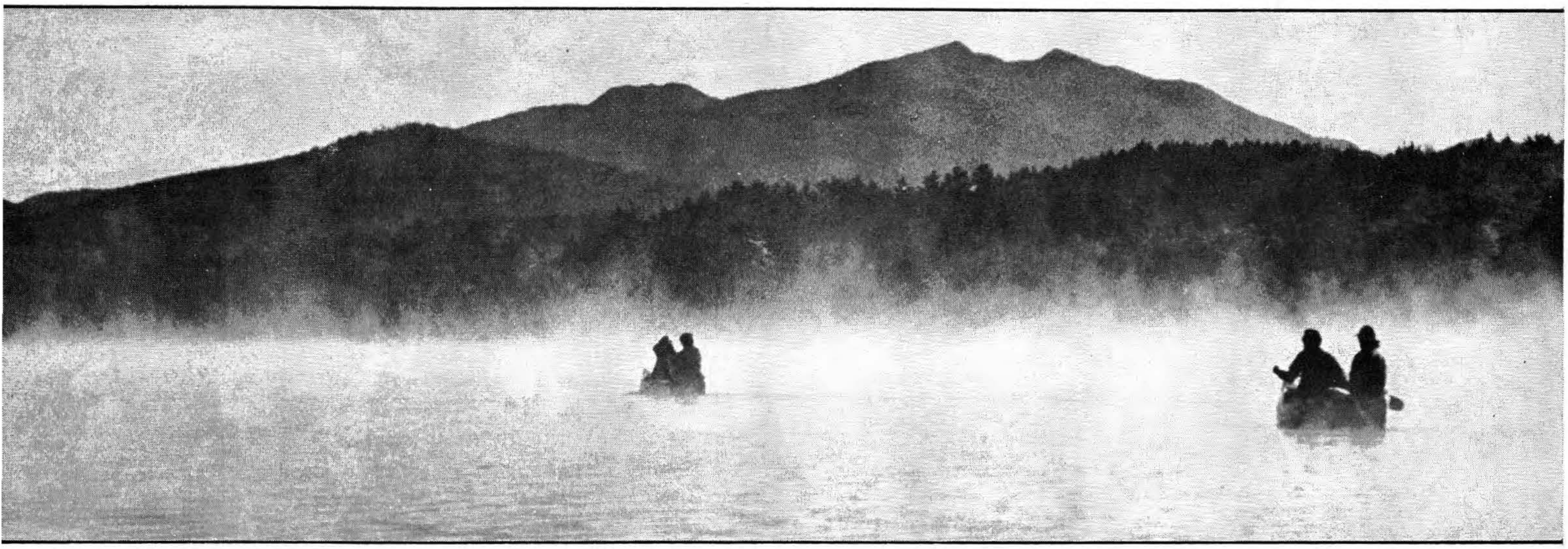


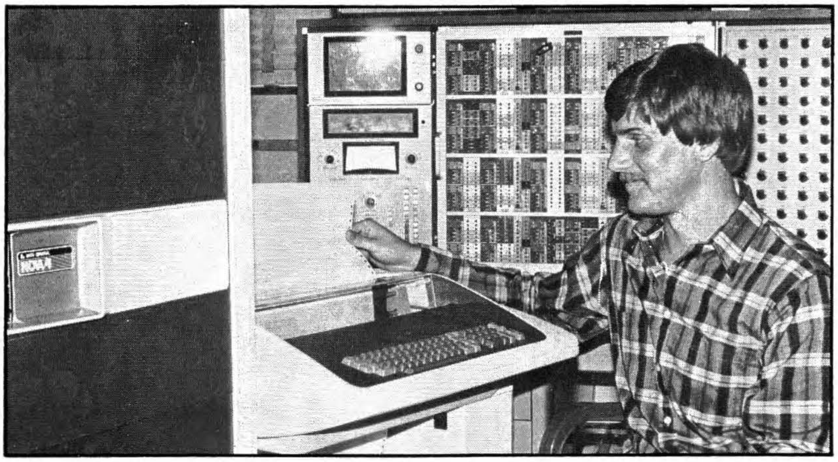
FOR ADMISSION INFORMATION

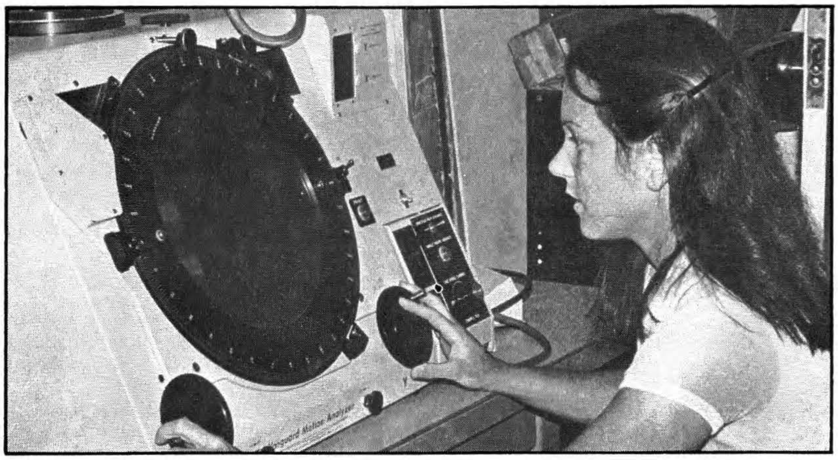
Chairman, Graduate Studies Committee
Chemical & Nuclear Engineering, #171
University of Cincinnati
Cincinnati, OH 45221

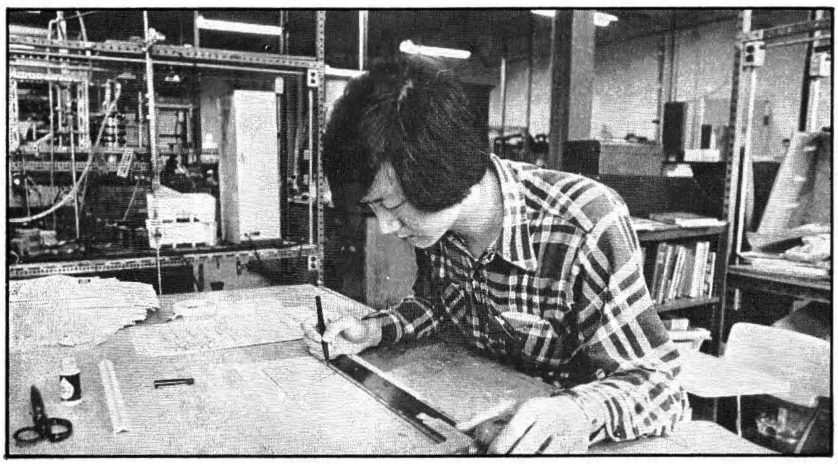
MEMBRANE SEPARATIONS

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

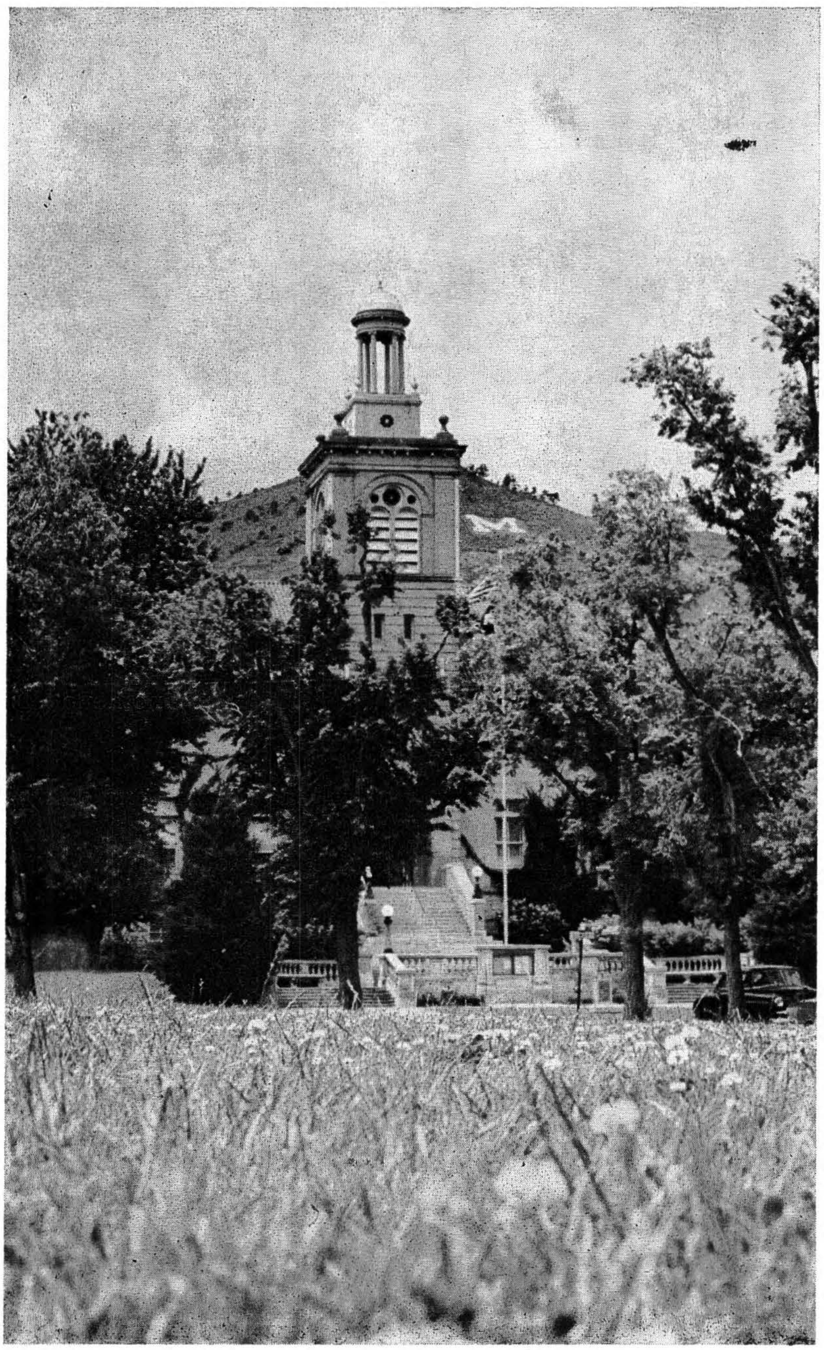








COLORADO SCHOOL OF MINES



THE FACULTY AND THEIR RESEARCH

P. F. Dickson, Professor and Head; Ph.D., University of Minnesota. Oil-shale, shale oil processing, petrochemical production from shale oil, heat transfer, heat exchanger design.

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.

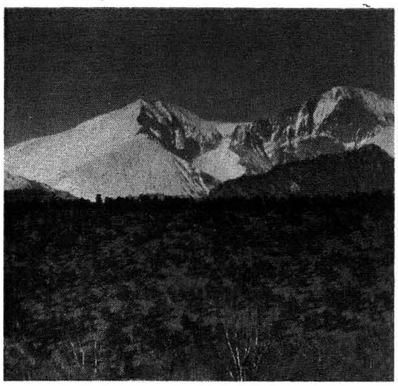
M. S. Selim, Associate Professor; Ph.D., Iowa State University. Flow of concentrated fine particulate suspensions in complex geometries; Sedimentation of multisized, mixed density particle suspensions.

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.

For Applications and Further Information On M.S., and Ph.D. Programs, Write

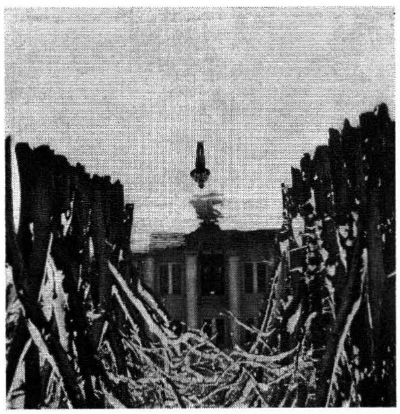
Chemical and Petroleum Refining Engineering
Colorado School of Mines
Golden, CO 80401

Colorado State University



Location:

CSU is situated in Fort Collins, a pleasant community of 78,000 people located about 65 miles north of Denver. This site is adjacent to the foothills of the Rocky Mountains in full view of majestic Long's Peak. The climate is excellent with 300 sunny days per year, mild temperatures and low humidity. Opportunities for hiking, camping, boating, fishing and skiing abound in the immediate and nearby areas. The campus is within easy walking or biking distance of the town's shopping areas and its new Center for the Performing Arts.



Degrees Offered:

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

Financial Aid Available:

Teaching and Research Assistantships paying a monthly stipend plus tuition reimbursement.

Faculty:

Larry Belfiore, Ph. D.,
University of Wisconsin

Bruce Dale, Ph.D.
Purdue University

Jud Harper, Ph.D.,
Iowa State University

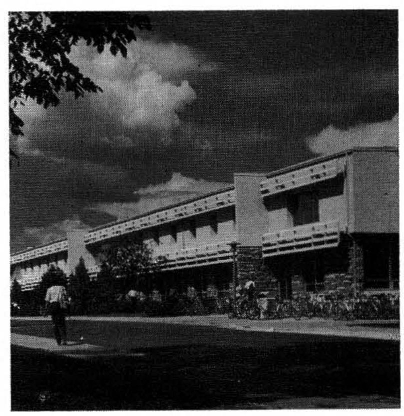
Naz Karim, Ph.D.,
University of Manchester

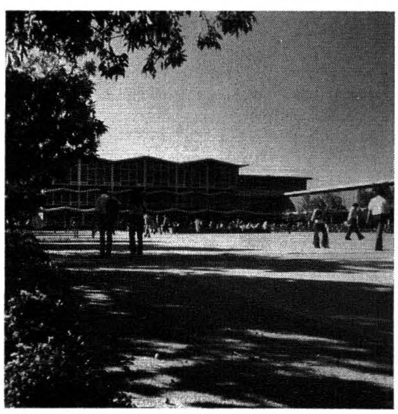
Terry Lenz, Ph.D.,
Iowa State University

Jim Linden, Ph.D.,
Iowa State University

Carol McConica, Ph.D.
Stanford University

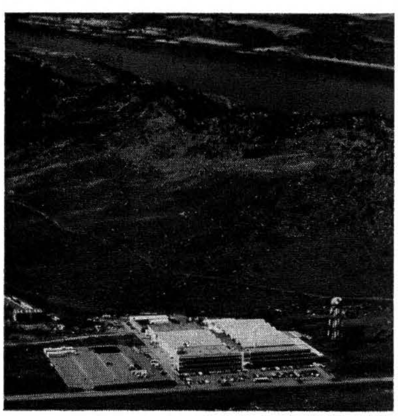
Vince Murphy, Ph.D.,
University of Massachusetts





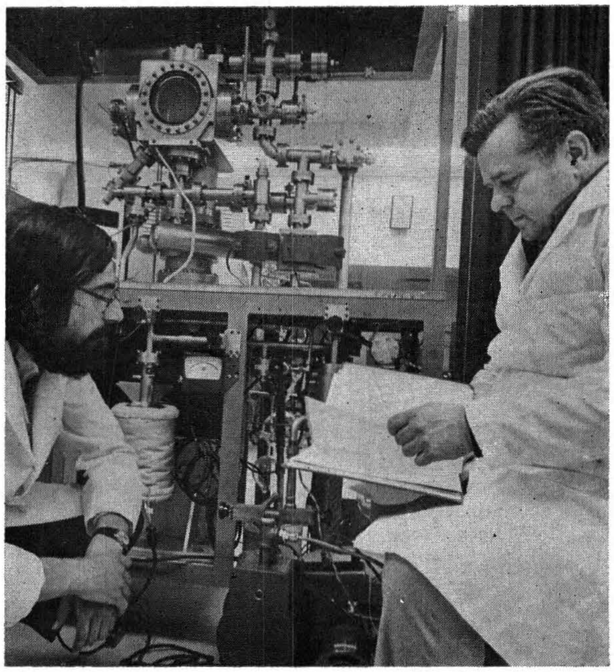
Research Areas:

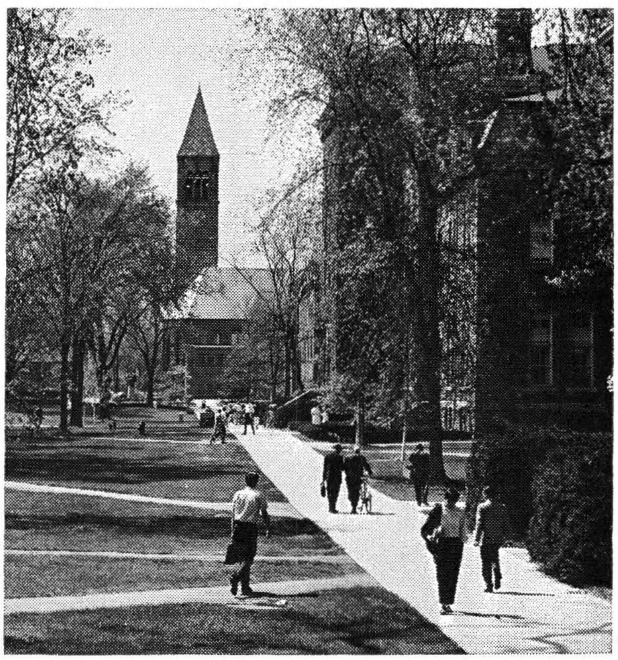
Alternate Energy Sources
Biochemical Engineering
Catalysis
Computer Simulation and Control
Fermentation
Food Engineering
Polymeric Materials
Porous Media Phenomena
Rheology
Solar Cooling Systems
Thermochemical Cycles
Wastewater Treatment

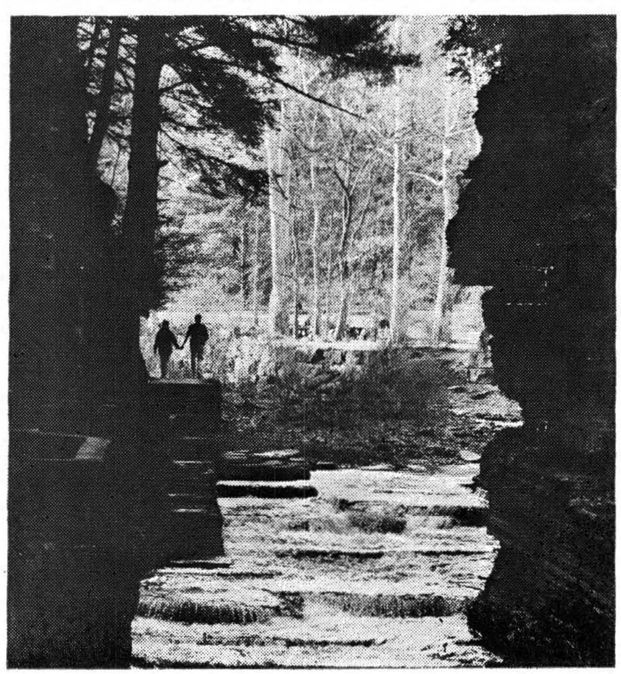


For Applications and Further Information, write:

Professor Vincent G. Murphy
Department of Agricultural and Chemical Engineering
Colorado State University
Fort Collins, CO 80523





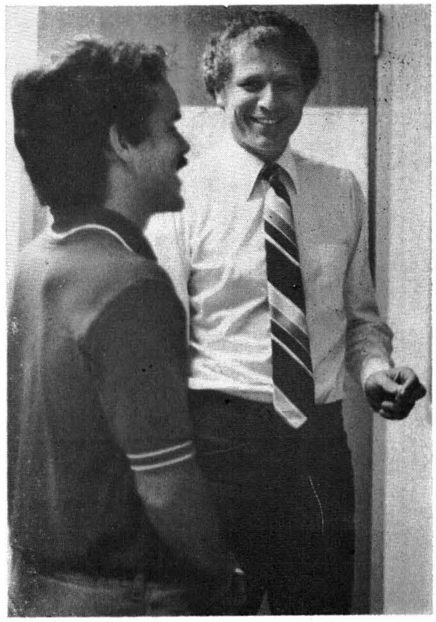


Graduate Programs in Chemical Engineering

University of Houston

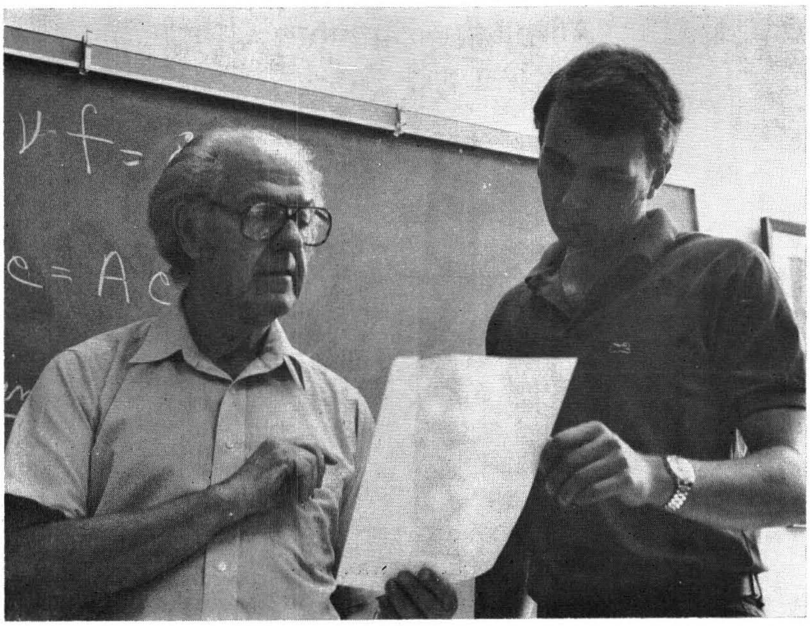
The Department of Chemical Engineering at the University of Houston has developed seven areas of special research strength:

- Chemical Reaction Engineering Catalysis
- Interfacial Phenomena, Rheology
- Two-phase Flow, Sedimentation
- Solid-liquid Separation
- Air Pollution Modeling
- Reliability Theory
- Petroleum Reservoir Engineering



The department occupies more than 64,000 square feet and is equipped with more than $2.5 million worth of experimental apparatus.

Financial suport is available to full-time graduate students with stipends ranging from $8,400 to $13,000 for twelve months.



The faculty:

N. R. Amundson
O. A. Asbjornsen
V. Balakotaiah
E. L. Claridge
J. R. Crump
H. A. Deans
A. E. Dukler
R. W. Flumerfelt
E. J. Henley
D. Luss
A. C. Payatakes
R. Pollard
H. W. Prengle, Jr.
J. T. Richardson
F. M. Tiller
J. Villadsen
F. L. Worley, Jr.

For more information or application forms write:
Director, Graduate Admissions
Department of Chemical Engineering
University of Houston
Houston, Texas 77004
(Phone 713/749-4407)

GRADUATE STUDY AND RESEARCH

The Department of Chemical Engineering

Graduate Programs in

The Department of Chemical Engineering

leading to the degrees of

MASTER OF SCIENCE and DOCTOR OF PHILOSPHY

THE UNIVERSITY OF ILLINOIS AT CHICAGO

FACULTY AND RESEARCH ACTIVITIES

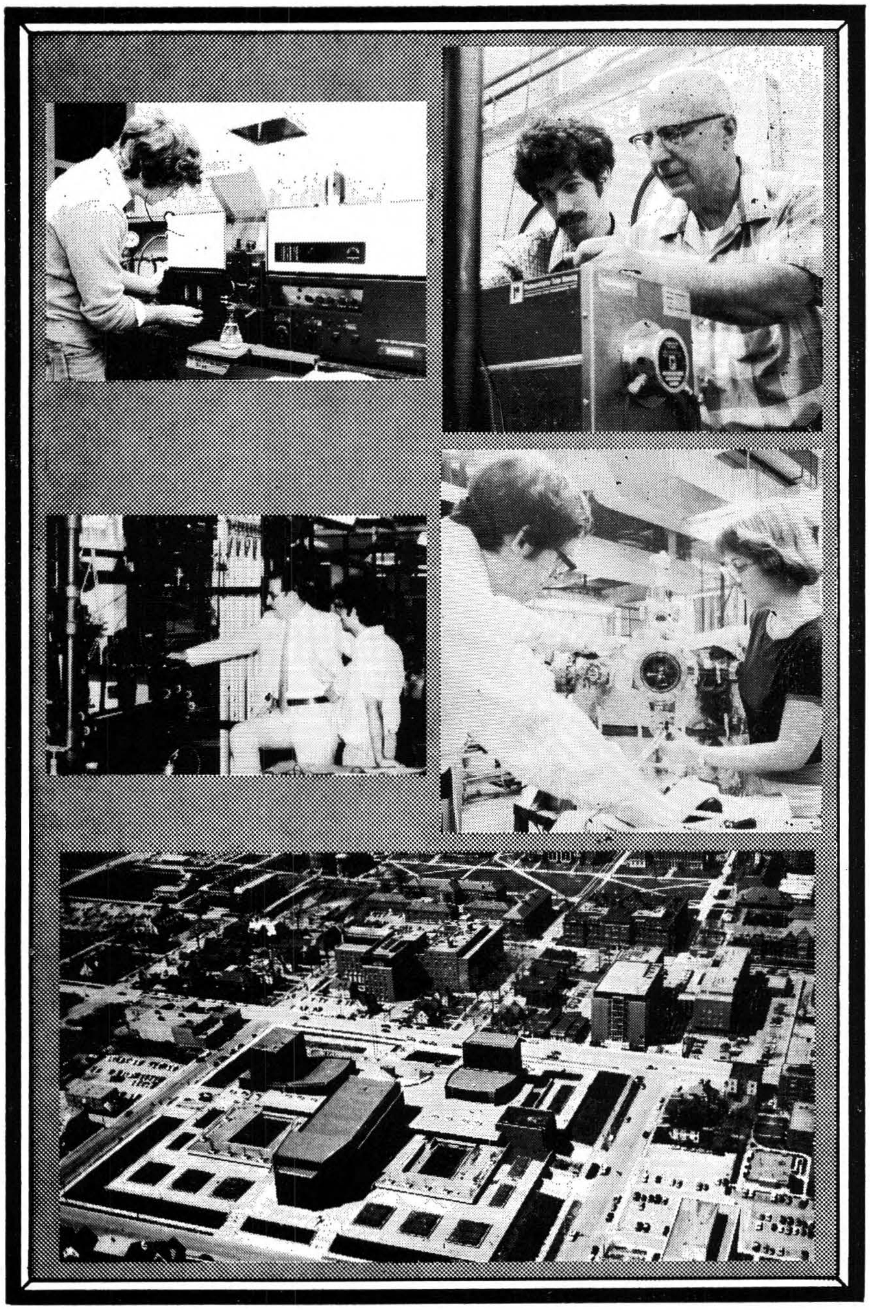
Francisco J. Brana-Mulero Ph.D., University of Wisconsin, 1980 Assistant Professor	Process synthesis, operations research, optimal process control, optimization of large systems, numerical analysis, theory of nonlinear equations.
T. S. Jiang PhD., Northwestern University, 1981 Asssitant Professor	Interfacial 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.

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

Professor S. Murad, Chairman

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



CHEMICAL ENGINEERING AT THE

UNIVERSITY OF ILLINOIS

URBANA CHAMPAIGN

For application forms and further information, write to:

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

FACULTY

Richard C. Alkire, Professor
Electrochemical Engineering

Harry G. Drickamer, Professor
High Pressure Studies, Structure and Properties of Solids

Charles A. Eckert, Professor and Head
Molecular Thermodynamics, Applied Chemical Kinetics

Thomas J. Hanratty, Professor
Fluid Dynamics, Convective Heat and Mass Transfer

Jonathan J. L. Higdon,
Assistant Professor
Fluid Mechanics, Applied Mathematics

Richard S. Larson,
Assistant Professor
Chemical Kinetics

Richard I. Masel,
Assistant Professor
Catalysis, Surface Science

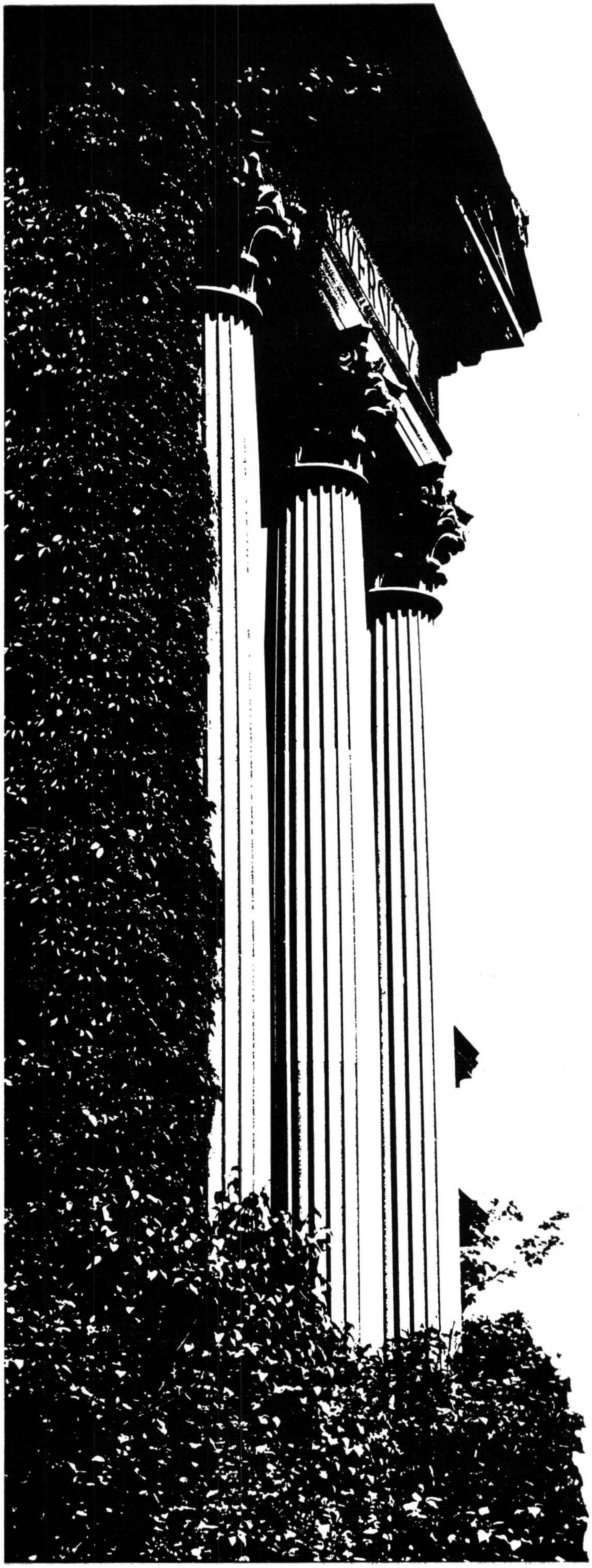
Walter G. May
Visiting Professor
Chemical Process Engineering

Anthony J. McHugh,
Professor
Polymer Crystallization, Transport of Particles

Joseph A. Shaeiwitz,
Assistant Professor
Mass Transfer, Interfacial and Colloidal Phenomena

Mark A. Stadtherr,
Associate Professor
Process Flowsheeting and Optimization

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



Iowa State University

Iowa State is an excellent place for your graduate study. Our facilities are first-rate and our support for graduate students is provided by the Engineering Research Institute, the Ames Laboratory of the Department of Energy and over 30 industrial firms. We are located in Ames, a town of about 46,000 offering a wide variety of outstanding cultural activities.

Please write:
Chair
Department of Chemical Engineering
Iowa State University
Ames, Iowa 50011

Faculty

William H. Abraham	(Purdue)
Renato G. Bautista	(Wisconsin)
Kris A. Berglund	(Iowa State)
Lawrence E. Burkhart	(Iowa State)
George Burnet	(Iowa State)
Charles E. Glatz	(Wisconsin)
James C. Hill	(Washington)
Kenneth R. Jolls	(Illinois)
Terry S. King	(MIT)
Maurice A. Larson	(Iowa State)
Allen H. Pulsifer	(Syracuse)
Peter J. Reilly	(Pennsylvania)
Glenn L. Schrader	(Wisconsin)
Richard C. Seagrave	(Iowa State)
Dean L. Ulrichson	(Iowa State)
Thomas D. Wheelock	(Iowa State)

Research Interests

Biochemical Engineering
Biomedical Engineering
Catalysis and Kinetics
Coal Technology
Crystallization Technology
Energy Conversion
Fluid Mechanics and Rheology
Heat Transfer
Mass Transfer
Polymer Technology
Process Instrumentation, Optimization and Control
Surface Science
Thermodynamics

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.

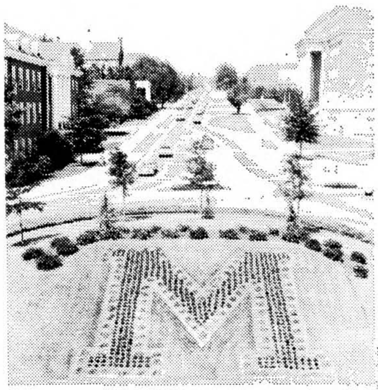
THE COMMUNITY

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 Maryland



Location:

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.

Degrees Offered:

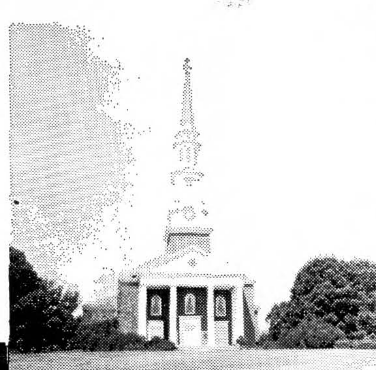
M.S. and Ph.D. programs in Chemical Engineering.

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
Larry L. Gasner
James W. Gentry
Albert Gomezplata
Randolph T. Hatch
Juan Hong
Thomas J. McAvoy
Thomas M. Regan
Wilburn C. Schroeder
Theodore G. Smith
Robert White



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. KITTRELL (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 •

J. C. W. CHIEN
Polymerization catalysts, Biopolymers, Polymer degradation

R. FARRIS
Polymer composites, Mechanical properties, Elastomers

S. L. HSU
Polymer spectroscopy, Polymer structure analysis

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

CHEMICAL ENGINEERING AT MIT

FACULTY

J. Wei, Department Head
M. Alger
R. C. Armstrong
R. F. Baddour
J. M. Beér
J. F. Brady
H. Brenner
R. A. Brown
R. E. Cohen
C. K. Colton
C. Cooney
W. M. Deen
L. B. Evans
T. A. Hatton
H. C. Hottel
J. B. Howard
G. A. Huff, Jr.
M. Kramer
J. P. Longwell
H. P. Meissner
E. W. Merrill
C. M. Mohr
R. C. Reid
A. F. Sarofim
C. N. Satterfield
H. H. Sawin
K. A. Smith
U. W. Suter
J. W. Tester
P. S. Virk
J. E. Vivian
D. I. C. Wang
G. C. Williams

RESEARCH AREAS

Biomedical Engineering
Biotechnology
Catalysis and Reaction Engineering
Combustion
Computer-Aided Design
Electrochemistry
Energy Conversion
Environmental
Fluid Mechanics
Integrated Circuit Processing
Kinetics and Reaction Engineering
Polymers
Process Dynamics and Control
Surfaces and Colloids
Transport Phenomena

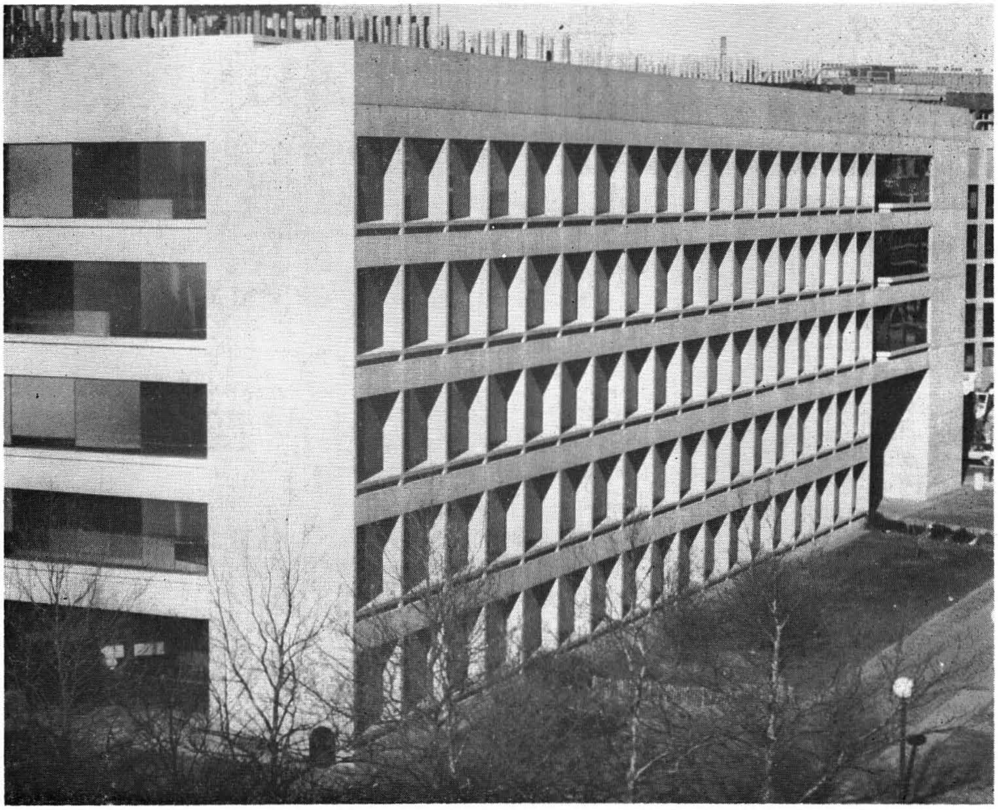


Photo by James Wei

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

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)—Kinetcis, 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)—Multistage Mass Transfer Operations, Distillation, Extraction, Process Control.

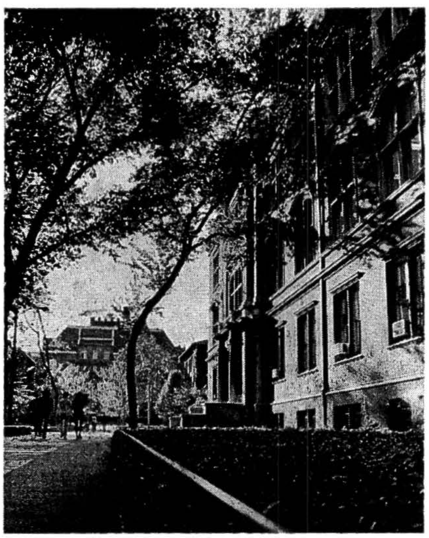
H. K. YASUDA (Ph.D., New York-Syracuse)—Polymer Membrane Technology, Thin-Film Technology, Plasma Polymerization, Biomedical Materials.

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


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

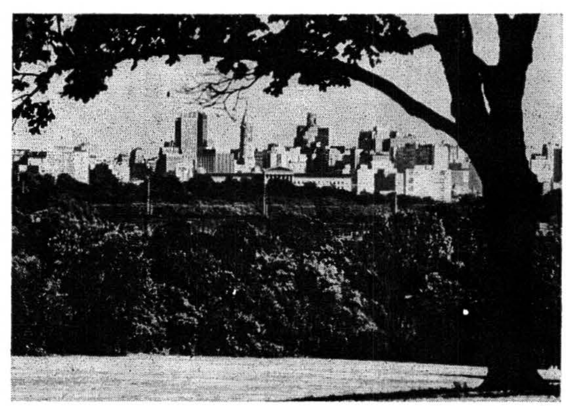
university of

pennsylvania chemical engineering



FACULTY

Stuart W. Churchill, PhD, Michigan (1952)
Elizabeth B. Dussan V., PhD, Johns Hopkins (1972)
Gregory C. Farrington, PhD, Harvard (1972)
William C. Forsman, PhD, Pennsylvania (1961)
Eduardo D. Glandt, PhD, Pennsylvania (1977)
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)
Alan L. Myers, PhD, California (1964)
Melvin C. Molstad, Emeritus
Daniel D. Perlmutter, PhD, Yale (1956)
John A. Quinn, PhD, Princeton (1959)—Chairman
Warren D. Seider, PhD, Michigan (1966)
Lyle H. Ungar, PhD, MIT (1983)



RESEARCH AREAS

Applied Mathematics
Biochemical Engineering
Biomedical Engineering
Chemical Reactor Engineering
Combustion
Computer-Aided Design
Crystal Growth
Electrochemistry
Fluid Mechanics
Heterogeneous Catalysis
Interfacial Phenomena
Membrane Transport
Numerical Analysis
Polymer Science
Reaction Kinetics
Separation Techniques
Solar Energy
Surface Phenomena
Thermodynamics
Transport Phenomena

Pennsylvania's chemical engineering program is designed to be flexible while emphasizing the fundamental nature of chemical and physical processes. Students may focus their studies in any of the research areas of the department. The full resources of this Ivy League university, including the Wharton School of Business and one of this country's foremost medical centers, are available to students in the program.

PHILADELPHIA:

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

For additional information, write:

Director of Graduate Admissions
Department of Chemical Engineering
School of Engineering and Applied Science
311A Towne Building/D3
University of Pennsylvania
Philadelphia, Pennsylvania 19104

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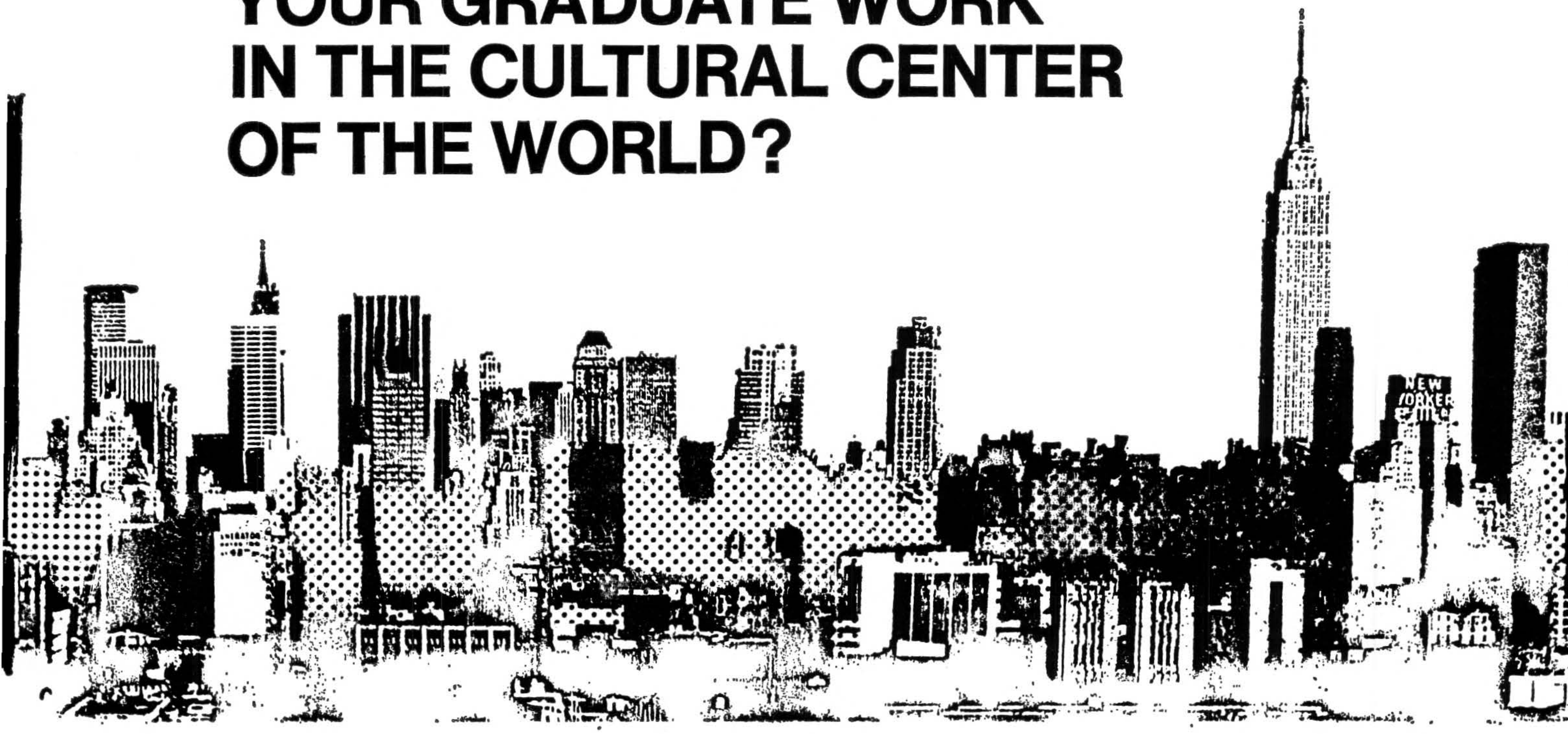

CHEMICAL ENGINEERING

POLYMER SCIENCE & ENGINEERING

FACULTY

R. C. Ackerberg
R. F. Benenati
J. J. Conti
C. D. Han
W. H. Kapfer
J. S. Mijovic
E. M. Pearce
E. Sadle
L. I. Stiel
C. G. Wan
E. N. Ziegler

RESEARCH AREAS

Biochemical Engineering
Catalysis, Kinetics and Reactors
Computer Aided Process Design
Energy Conversion
Engineering Properties of Polymers
Fluidization
Fluid Mechanics
Heat and Mass Transfer
Polymer Processing
Polymer Morphology
Polymer Synthesis and Modification
Polymerization Reaction Engineering
Rheology
Separation Sciences
Thermodynamic Properties of Fluids

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Department of Chemical Engineering

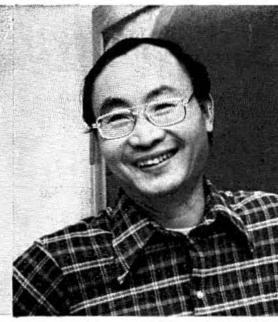
Programs leading to Master's and Doctor's degrees. Areas of study and research: chemical engineering, polymer science and engineering.

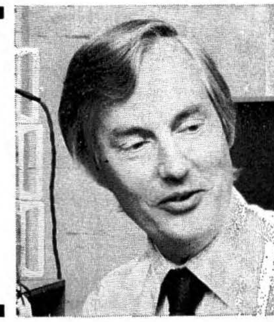
Fellowships and Research Assistantships are available.

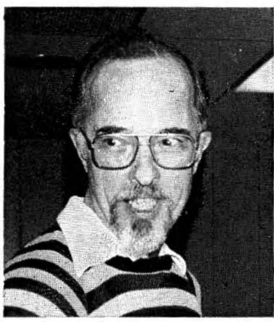
For further information contact

Professor R. F. Benenati
Head, Department of Chemical Engineering
Polytechnic Institute of New York
333 Jay Street
Brooklyn, New York 11201

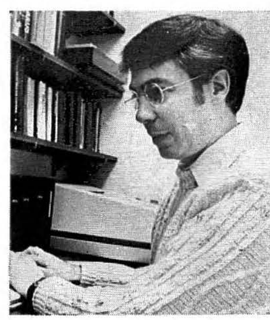


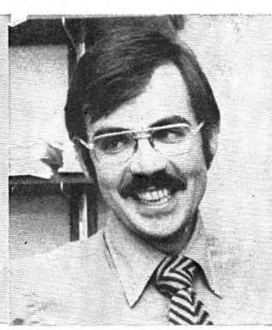





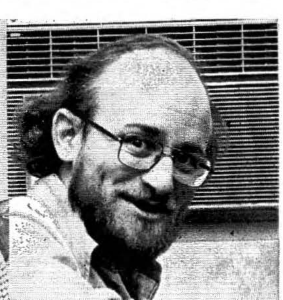






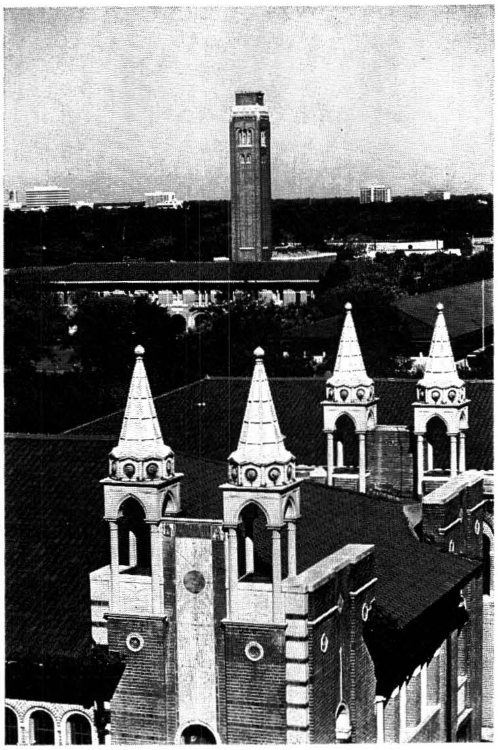







Rice University

Graduate Study in Chemical Engineering



THE UNIVERSITY

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- 2600 undergraduate students
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THE CITY

- Large metropolitan and cultural center
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THE DEPARTMENT

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- M.D.-M.S. and M.D.-Ph.D. degrees available through joint program with Baylor College of Medicine
- Approximately 80 graduate students (predominately Ph.D.)
- 13 full-time faculty
- Tax-free stipends and tuition waivers for full-time students
- Special fellowships with higher stipends for outstanding candidates

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

Chairman, Graduate Committee
Department of Chemical Engineering
Rice University
Houston, TX 77251

Graduate Study in Chemical Engineering at

SYRACUSE UNIVERSITY

THE DEPARTMENT

- Close relationship between faculty and graduate students
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THE UNIVERSITY

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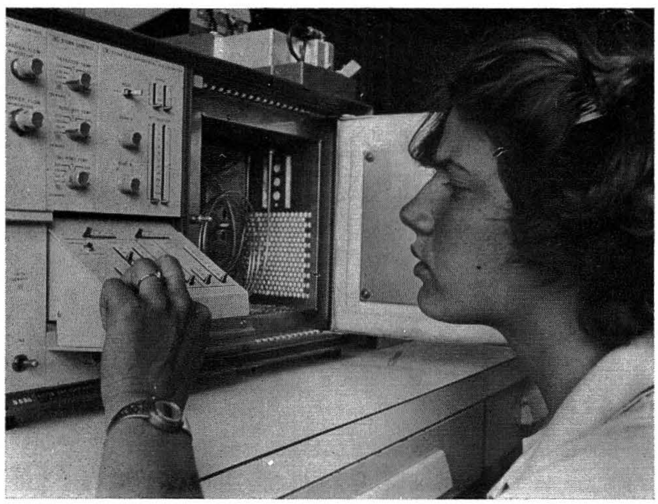
FELLOWSHIPS AND GRADUATE ASSISTANTSHIPS AVAILABLE

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	Biotransport 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
Chiu-sen Wang	Aerosol Technology



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

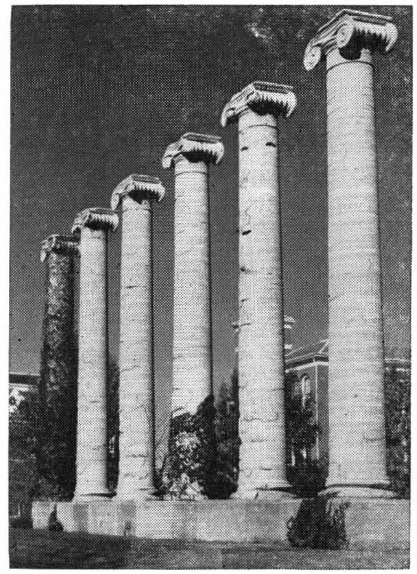
C. D. Holland (department head)—distillation
A. Akgerman—kinetics
R. G. Anthony—catalysis
D. B. Bukur—reaction engineering
J. A. Bullin—gas sweetening, air pollution
R. Darby—rheology
R. R. Davison—solar energy
L. D. Durbin—process control
P. T. Eubank—thermodynamics
T. W. Fogwell—applied mathematics
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

UNIVERSITY OF MISSOURI - COLUMBIA

DEPARTMENT OF CHEMICAL ENGINEERING



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

Research Areas

Air Pollution Monitoring and Control
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
Themodynamics 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

OFFERING GRADUATE STUDY AND RESEARCH IN:

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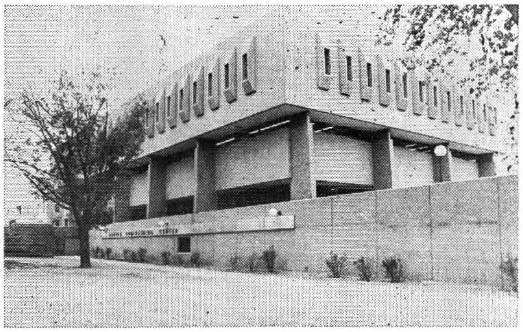
- Bio-mass Conversion
- Reaction Kinetics
- Real-time Computing
- Polymer Engineering
- Separation Processes
- Surface Science
- Thermodynamics and Phase Equilibria

For Application and Information:
Chairman of Chemical Engineering
226 Avery Hall, University of Nebraska
Lincoln, Nebraska 68588-0126

THE UNIVERSITY OF NEW MEXICO

M.S. and Ph.D. Graduate Studies in Chemical Engineering



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- **Desalination/Separation Processes**
- **Advanced Design Concepts**
- **Catalysis**
- **Synthetic Fuel Technology**
- **Mini Computer Applications to Process Control**
- **Process Simulation**
- **Hydro—Metallurgy**
- **Radioactive Waste Management**
- **Biomedical Systems**
- **Solar Ponds**

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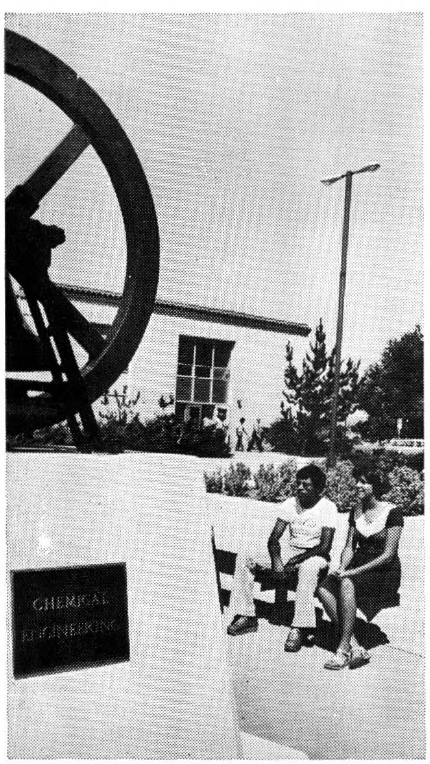
For further information, write:

Chairman, Graduate Committee
Dept. of Chemical and Nuclear Engineering
The University of New Mexico
Albuquerque, New Mexico 87131



Graduate study toward M.S. degrees in chemical engineering

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- *bioconversion*
- *petroleum*
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FOR APPLICATIONS AND INFORMATION:

Dr. John T. Patton, Head, Department of Chemical Engineering, Box 3805, New Mexico State University, Las Cruces, New Mexico 88003-3805

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GRADUATE STUDY IN CHEMICAL AND PETROLEUM ENGINEERING . . . .

UNIVERSITY OF PITTSBURGH

The Department of Chemical and Petroleum Engineering awards Master of Science and Doctor of Philosophy degrees through flexible full and part-time programs accommodating the needs of a wide range of engineering professionals. The general objective of all programs is to develop the ability of the chemical or petroleum engineer to carry out design and original research at advanced levels.

Within the department there are currently 16 faculty members, five visiting scholars, four post-doctoral fellows, 77 full-time and 40 part-time graduate students, and 300 undergraduates.

The department is housed on the top two floors of Benedum Hall. In addition, the Unit Operations Laboratory and many research labs utilizing high-pressure or large equipment are situated in the sub-basement.

FACULTY

Charles S. Beroes
Paul Biloen
Alfred A. Bishop
Alan J. Brainard
Shiao-Hung Chiang
James T. Cobb, Jr.
Paul F. Fulton
James G. Goodwin
Gerald D. Holder
George E. Klinzing
Joseph H. Magill
Badie Morsi
Alan A. Reznik
Yatish T. Shah
John W. Tierney
Irving Wender

PROGRAMS AND SUPPORT

Master of Science and Doctor of Philosophy degrees in Chemical Engineering and Master of Science degree in Petroleum Engineering are offered. While obtaining advanced degrees, students may specialize in research in Energy-related Fields, Transport Phenomena, Interphase Transport, Process Modeling and Synthesis, Thermodynamics, Reactor Engineering and Catalysis.
Dual degrees are offered in Chemical/Petroleum and engineering/Mathematics.

Graduate applicants should write:

Graduate Coordinator, Chemical and Petroleum Engineering
School of Engineering
University of Pittsburgh
Pittsburgh, PA 15261

Princeton University M.S.E. AND Ph.D. PROGRAMS IN CHEMICAL ENGINEERING

RESEARCH AREAS

Catalysis; Chemical Reactor/Reaction Engineering; Energy Conversion and Fusion Reactor Technology; Colloidal Phenomena; Environmental Studies; Fluid Mechanics and Rheology; Hazardous Wastes; Mass and Momentum Transport; Polymer Materials Science and Rheology; Process Control; Geothermal Processes; Flow of Granular Media; Statistical Mechanics; Surface Science; Thermodynamics and Phase Equilibria.

FACULTY

Robert C. Axtmann, Jay B. Benziger, John K. Gillham, Carol K. Hall, Roy Jackson, Ernest F. Johnson, Jeffrey Koberstein, Morton D. Kostin, Bryce Maxwell, Robert G. Mills, Robert K. Prud'homme, Ludwig Rebenfeld, William B. Russel, Dudley A. Saville, William R. Schowalter (Chairman), Sankaran Sundaresan.

WRITE TO

Director of Graduate Studies
Chemical Engineering
Princeton University
Princeton, New Jersey 08544

UNIVERSITY OF SOUTHERN CALIFORNIA
Los Angeles
Graduate Study in Chemical Engineering

- Interested in advanced studies for the M.S., Eng. or Ph.D. degree in Chemical Engineering?
- Interested in a dynamic and growing department in one of the World's great climates and metropolitan areas?
- If so, write for further information about the program, financial support, and application forms to:

Graduate Admissions
Department of Chemical Engineering
University of Southern California
University Park,
Los Angeles, CA 90089-1211

FACULTY

WENJI VICTOR CHANG
(Ph.D., Ch.E., Caltech, 1976)
Rheological properties of polymers and composites, adhesion, polymer processing

JOE D. GODDARD
(Ph.D., Ch.E., U.C. Berkeley, 1962)
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