



## GRADUATE EDUCATION ISSUE

### *Featuring . . .*

A Course on Parallel Computing  
**Kim**

A Pilot Graduate-Recruiting Program  
**Sloan, Baldwin, Fiedler, McKinnon, Miller**

A Course on Environmental Remediation  
**Stokes**

A Colloquium Series in Chemical Engineering  
**Tsouris, Yiacoymi, Hirtzel**

Research on Neural Networks, Optimization, and Process Control  
**Cooper, Achenie**

Chemical Reaction Engineering: A Story of Continuing Fascination  
**Doraiswamy**

Pattern Formation in Convective-Diffusive Transport With Reaction  
**Arce, Locke, Viñals**

An Introduction to the Fundamentals of Bio(Molecular) Engineering  
**Locke**

Some Thoughts on Graduate Education: A Graduate Student's Perspective  
**Kannan**

### *And also . . .*

Problem: The Influence of Catalysts on Thermodynamic Equilibrium  
**Falconer**

Random Thoughts: Sorry, Pal—It Doesn't Work That Way  
**Felder**

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## Editor's Note to Seniors . . .

This is the 26th graduate education issue published by CEE. It is distributed to chemical engineering seniors interested in and qualified for graduate school. We include articles on graduate courses and research at various universities, along with departmental announcements on graduate programs. In order for you to obtain a broad idea of the nature of graduate work, we encourage you to read not only the articles in this issue, but also those in previous issues. A list of the papers from recent years follows. If you would like a copy of a previous fall issue, please write to CEE.

Ray W. Fahien, Editor

### Fall 1991

- Carnahan • *Computing in Engineering Education: From There, To Here, To Where? (Award Lecture, Part 1)*  
Deshpande, Krishnaswamy • *A Graduate Course in Digital Computer Process Control*  
Churchill • *Chemical Kinetics, Fluid Mechanics and Heat Transfer in the Fast Lane*  
Fleischman • *Risk Reduction in the Chemical Engineering Curriculum*  
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Peters • *An Introduction to Molecular Transport Phenomena*

### Fall 1990

- Austin, Beronio, Taso • *Biochemical Engineering Education Through Videotapes*  
Ramkrishna • *Applied Mathematics*  
Rice • *Dispersion Model Differential Equation for Packed Beds*  
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Cohen, Tsai, Chetty • *Multimedia Environmental Transport, Exposure, and Risk Assessment*  
Schulz, Bengel • *ChE Summer Series at Virginia Polytechnic*  
Roberge • *Transferring Knowledge*  
Coulman • *ChE Curriculum, 1989*  
Frey • *Numerical Simulation of Multicomponent Chromatography Using Spreadsheets*  
Fried • *Polymer Science and Engineering at Cincinnati*

### Fall 1989

- San, McIntire • *Biochemical and Biomedical Engineering*  
Kummier, McMicking, Powitz • *Hazardous Waste Management*  
Bienkowski, et al. • *Multidisciplinary Course in Bioengineering*  
Lauffenburger • *Cellular Bioengineering*  
Randolph • *Particulate Processes*  
Kumar, Bennett, Gudivaka • *Hazardous Chemical Spills*  
Davis • *Fluid Mechanics of Suspensions*  
Wang • *Applied Linear Algebra*  
Kisaalita, et al. • *Crossdisciplinary Research: The Neuron-Based Chemical Sensor Project*  
Kyle • *The Essence of Entropy*  
Rao • *Secrets of My Success in Graduate School*

### Fall 1988

- Arkun, Charos, Reeves • *Model Predictive Control*  
Briedis • *Technical Communications for Grad Students*  
Deshpande • *Multivariable Control Methods*  
Glandt • *Topics in Random Media*  
Ng, Gonzalez, Hu • *Biochemical Engineering*  
Goosen • *Research: Animal Cell Culture in Microcapsules*  
Teja, Schaeffer • *Research: Thermodynamics and Fluid Properties*  
Duda • *Graduation: The Beginning of Your Education*

### Fall 1992

### Fall 1987

- Amundson • *American University Graduate Work*  
DeCoursey • *Mass Transfer with Chemical Reaction*  
Takoudis • *Microelectronics Processing*  
McCready, Leighton • *Transport Phenomena*  
Seider, Ungar • *Nonlinear Systems*  
Skaates • *Polymerization Reactor Engineering*  
Edie, Dunham • *Research: Advanced Engineering Fibers*  
Allen, Petit • *Research: Unit Operations in Microgravity*  
Bartusiak, Price • *Process Modeling and Control*  
Bartholomew • *Advanced Combustion Engineering*

### Fall 1986

- Bird • *Hougen's Principles*  
Amundson • *Research Landmarks for Chemical Engineers*  
Auda • *Graduate Studies: The Middle Way*  
Jorne • *Chemical Engineering: A Crisis of Maturity*  
Stephanopoulos • *Artificial Intelligence in Process Engineering*  
Venkatasubramanian • *A Course in Artificial Intelligence in Process Engineering*  
Moo-Young • *Biochemical Engineering and Industrial Biotechnology*  
Babu, Sukanek • *The Processing of Electronic Materials*  
Datye, Smith, Williams • *Characterization of Porous Materials and Powders*  
Blackmond • *A Workshop in Graduate Education*

### Fall 1985

- Bailey, Ollis • *Biochemical Engineering Fundamentals*  
Belfort • *Separation and Recovery Processes*  
Graham, Jutan • *Teaching Time Series*  
Soong • *Polymer Processing*  
Van Zee • *Electrochemical and Corrosion Engineering*  
Radovic • *Coal Utilization and Conversion Processes*  
Shah, Hayhurst • *Molecular Sieve Technology*  
Bailie, Kono, Henry • *Fluidization*  
Kauffman • *Is Grad School Worth It?*  
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### Fall 1984

- Lauffenburger, et al. • *Applied Mathematics*  
Marnell • *Graduate Plant Design*  
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Shah • *Heterogeneous Catalysis with Video-Based Seminars*  
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**THIRTIETH ANNUAL LECTURESHIP AWARD TO  
WILLIAM N. GILL**

The 1992 ASEE Chemical Engineering Division Lecturer is **William N. Gill** of Rensselaer Polytechnic Institute. The purpose of this award is to recognize and encourage outstanding achievement in an important field of fundamental chemical engineering theory or practice.

The award, an engraved certificate, is bestowed annually upon a distinguished engineering educator who delivers the annual lecture of the Chemical Engineering Division. This year it was presented to the winner at the Division's summer school, held at Montana State University in August. The award is made on an annual basis, with nominations welcomed through February 1, 1993.

Dr. Gill's lecture was entitled "Interactive Dynamics of Convection and Crystal Growth." It will be published in a forthcoming issue of *CEE*.

**Award Winners**

There were a number of significant awards presented to chemical engineering faculty members during the annual conference held at the University of Toledo in June, 1992. **Robert A. Greenkorn** (Purdue University) was named a Fellow of ASEE, having met the requirements of Fellow Grade membership as stated in the ASEE Constitution. The Fred Merryfield Design Award was presented to **Klaus D. Timmerhaus** (University of Colorado), recognizing his sustained excellent in engineering education and particularly his contributions to teaching chemical engineering design.

**Douglas A. Lauffenburger** (University of Illi-

nois, Urbana-Champaign) received the Curtis W. McGraw Research Award in recognition of his many outstanding achievements and, in particular, for expanding the boundaries of engineering research and education by using engineering principles and approaches in cell biology research. The George Westinghouse Award was presented to **Nicholas A. Peppas** (Purdue University) for his outstanding, innovative contributions to engineering education during his fifteen-year tenure at Purdue University.

**C. Stewart Slater** (Manhattan College) received the Fluke Award for Excellence in Laboratory Instruction, recognizing his contributions in the promotion of excellence in experimentation and laboratory instruction. The Dow Outstanding Young Faculty Award for the North Central Section went to **J. Richard Elliot, Jr.** (University of Akron), and **Robert M. Ybarra** (University of Missouri, Rolla) received a plaque naming him as an Outstanding Zone Campus Representative for Zone III.

**ChE Division Officers**

The 1992-93 officers for the Chemical Engineering Division of ASEE are:

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**Note to Our Readers:**

*It is with pride that we announce that our editor, Ray W. Fahien, is the 1992 recipient of the prestigious AIChE Warren K. Lewis award. This singular recognition for his contributions to chemical engineering over the years is well deserved and gives due testimony to his devotion to the profession and his adherence to its highest standards of excellence. Those of us who work closely with him want to add our congratulations and appreciation for his unselfish and high-minded leadership through the years, and the grace with which he has conducted himself in all matters.*

Tim Anderson, Associate Editor

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CHEMICAL ENGINEERING EDUCATION (ISSN 0009-2479) is published quarterly by the Chemical Engineering Division, American Society for Engineering Education, and is edited at the University of Florida. Correspondence regarding editorial matter, circulation, and changes of address should be sent to CEE, Chemical Engineering Department, University of Florida, Gainesville, FL 32611. Copyright © 1992 by the Chemical Engineering Division, American Society for Engineering Education. The statements and opinions expressed in this periodical are those of the writers and not necessarily those of the ChE Division, ASEE, which body assumes no responsibility for them. Defective copies replaced if notified within 120 days of publication. Write for information on subscription costs and for back copy costs and availability. POSTMASTER: Send address changes to CEE, Chemical Engineering Department, University of Florida, Gainesville, FL 32611.

# A Course on . . .

## PARALLEL COMPUTING

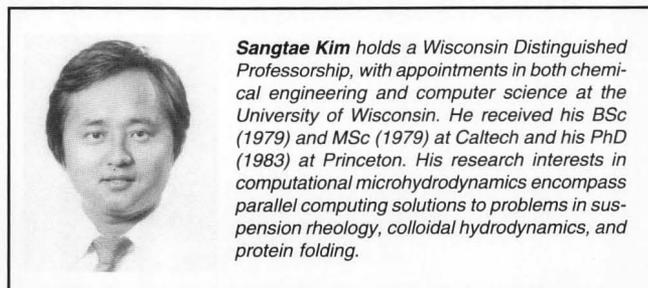
SANGTAE KIM

University of Wisconsin  
Madison, WI 53706

Parallel computing has received considerable and favorable attention in sources ranging from chemical engineering literature<sup>[1]</sup> to the popular media (see Figure 1). A new course on parallel computing has been developed at the University of Wisconsin that meets the needs of both graduate and advanced undergraduate engineering students.

Why the sudden surge in interest in parallel computing? As a concept, parallel computing has been around for several decades. As early as 1966, Flynn<sup>[2]</sup> delineated some of the key features found in a parallel computer. However, the rapid evolution of uniprocessor speeds squeezed the window for design and development of parallel computers. The reasoning went that during the three to five years over which a system was designed and developed, its processor components would be outclassed by a new generation of uniprocessors. But the pace of uniprocessor evolution is certainly slowing at the high end. Figure 2 compares the evolution in computing capabilities of the fastest uniprocessors and a square inch of silicon during the 1980s.

The performance of a single fast superprocessor is ultimately bound by fundamental physical constraints, such as the speed of light. So we turn instead to the idea of connecting very many rela-



tively inexpensive processors, an idea that becomes increasingly more practical as the processing capability on a square inch of silicon approaches the 100 MegaFLOPS benchmark—a traditional unit measure of supercomputing performance. Indeed, with shrinking semiconductor dimensions, it is quite likely that in the near future a square inch of silicon will house four, and then sixteen, such processors. Thus, in Figure 2 one could extrapolate the upward slope of the semiconductor processor curve well into the 1990s.

The emergence of the *high-performance parallel computer* creates new opportunities for science and engineering, and new courses must be developed to train the next generation of scientists and engineers. The challenge is twofold: to map currently popular solution methodologies to parallel algorithms and to develop new solution methods that naturally lead to parallel algorithms.



Figure 1. Doonesbury cartoon  
(DOONESBURY copyright 1992 G.B. Trudeau. Reprinted with permission of UNIVERSAL PRESS SYNDICATE. All rights reserved.)

The course consists of three parts, . . . an introduction to parallel computing architectures, followed by an overview of parallel computing extensions of high-level languages . . . [and] term projects on various parallel computers in which students get first-hand opportunities to implement the ideas . . .

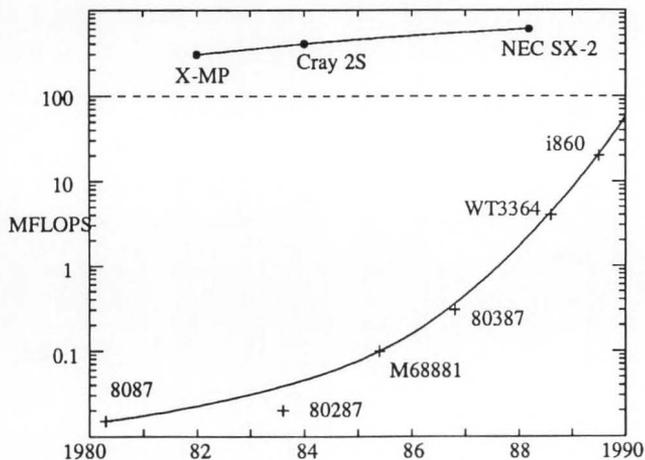


Figure 2. Evolution of floating point performance during the 1980s. 1000 x 1000 LINPACK, from Dongarra.<sup>[3]</sup>

The course consists of three parts, starting with an introduction to parallel computing architectures, followed by an overview of parallel computing extensions of high-level languages like Fortran. The third part consists of term projects on various parallel computers in which students get first-hand opportunities to implement the ideas discussed in the first and second parts of the course.

The course begins with a survey of historical and philosophical perspectives on parallel computing, as summarized in an excellent series of essays in *DÆDALUS*, the Journal of the American Academy of Arts and Sciences.<sup>[4]</sup> Some essays compare and contrast the development and societal impact of the first digital electronic computers and the corresponding changes wrought by the emergence of the massively parallel computer. Other essays provide benchmark comparisons of conventional vector supercomputers, RISC workstations, and parallel machines on a suite of computational tasks. Students are also directed to historical accounts of the founding of the major players in the parallel computing market.<sup>[5]</sup>

The course then shifts into an introductory description of parallel computer architectures. The concept of algorithm and machine granularity (fine grain and coarse grain parallelism) styles of control (SIMD, MIMD), and memory layout (Shared, Distributed-Message Passing) are reviewed. The book by

Bertsekas and Tsitsiklis<sup>[6]</sup> is used as a guide. The concepts are illustrated with specific examples involving Bus-based architectures (Cray, Alliant), SIMD computing on the Thinking Machine Corporation CM2, and message passing on the Intel iPSC/860 hypercube.

The discussion on parallel computing with high-level languages centers around parallel extensions of the Fortran language. The paradigm for shared memory machines (shared common blocks, forking of child processes, barrier synchronization, spin locks) follows the discussion in Brawer,<sup>[7]</sup> and his standards are then compared with example Fortran codes on real machines (Sequent Symmetry, IBM 3090). Fortran extensions on message passing systems (node programs, host programs, synchronous and asynchronous sends and receives, waiting for messages) are illustrated with examples from the Intel iPSC/860 hypercube. Students monitor program performance on the iPSC/860 with execution trace files created by PICL<sup>[8]</sup> and subsequent visualization on Unix workstations with the ParaGraph software developed by Heath and coworkers.<sup>[9]</sup>

This section of the course then concludes with a discussion of Fortran90 and its close relative, CM Fortran. A four-hour videotape on CM Fortran implementation on the CM5 provided by the Thinking Machines Corporation was used. The coverage of Fortran90 was partly hampered by the lack of an inexpensive compiler for the workstation environment. However, we recently obtained the NAG Fortran90 compiler for our NeXTstations and plan to use it in the course next year.

A required project takes the last five weeks of the semester. A list of suggested projects is announced at the start of the semester so that students have ten weeks to pick their project and find their partner. Students are grouped in teams of two, and as far as possible undergraduates are paired with graduate students. Since twelve students (including five seniors) took the course in the spring of 1992, we had six teams and projects (see Table 1, next page). In general, project topics range from the adventurous (review and reproduction of parallel algorithms from the burgeoning literature on parallel computing) to the pragmatic (parallelization of codes from dissertation research) implementations on the iPSC/860 or the CM5. One team used both machines.

**TABLE 1**  
**Term Projects: Spring 1992**

- Parallel branch and bound for mixed integer linear programs
- Numerical implementation of conjugate gradient and Gaussian elimination methods on parallel computers
- Parallel computational solutions of hyperbolic PDEs (humidification waves in solar energy desiccants)
- Polyhedra in Stokes flow (particle simulations on the iPSC/860 and CM5)
- Molecular dynamics on the hypercube (simulation of Lennard-Jones fluids)
- Wavelet transforms for signal analysis (signal data compression)

Oral presentations, conducted during the last two weeks of the course, present students with the opportunity to learn from each other. A number of established techniques in the literature, as well as new tricks on a particular machine, are disseminated in these discussions. Course grades are computed on the basis of the oral presentation and written report.

At the end of the semester, the student evaluations were collected. On the basis of a very favorable response, it appears that this course will be a regular spring semester offering in the department (and in the college of engineering). Work is also underway to integrate this course into a multicourse sequence in parallel computing in the Computer Sciences Department. A two-day version

of the course is also available from the AIChE Continuing Education Division.<sup>[10]</sup>

One final note: computer programs developed for the term projects are archived on a file server for future reference. It is my intention to document the growth of the parallel computing culture by monitoring the evolution of student projects, in terms of style and level of sophistication, starting with what future generations may view as the dawn of the age of parallel computing.

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## ChE book review

### CHEMICAL ENGINEERING DESIGN PROJECT: A CASE STUDY APPROACH

by Martyn S. Ray and David W. Johnson  
Gordon and Breach Science Publishers, New York;  
357 pages, \$90 hardbound, \$65 softbound (1989)

Reviewed by  
James R. Fair  
The University of Texas at Austin

This text is intended for use in the senior design course for chemical engineering students. It offers an approach that is different from that of the usual design course text; whereas the others provide a general overview of the design process, this text deals in considerable depth with just one project—the development and design of a plant to produce

nitric acid from ammonia and air. The factors supporting this project are dealt with in considerably more detail than would be the case for the usual text.

The book is divided into two main parts plus a lengthy appendix. Part I covers general aspects of a proposed nitric acid plant: feasibility study, process selection, site location, preliminary process design, and economic evaluation. Part II covers detailed design aspects, with sub-case studies of the absorption column, the steam superheater, and a pump to remove liquid from the absorber. Appendix contents include supporting property and cost data and example equipment calculations. Notable, the book contains no information on capital or manufacturing cost estimating or profitability analysis. No mention is made of discounted cash flow, for example. How-

*Continued on page 189*

## SORRY, PAL— IT DOESN'T WORK THAT WAY

RICHARD M. FELDER  
North Carolina State University  
Raleigh, NC 27695-7905

---

■ Dear Professor Felder: Kindly review the enclosed 47-page manuscript, "A New and Much Longer Derivation of the Quantum Correction to Klezmer's Tensor Correlation for Nonnewtonian Flow of Molten Cheese in an Octagonal Orifice. Part 7: Effects of Sunspots." Sincerely, W. Schlepper, Editor, *Journal of Pretentious Fluid Mechanics*.

P.S. We are attempting to clear our inventory of back papers and so I would appreciate your returning the review by next Tuesday.

---

■ . . . and I know I got a 36 on the final exam, Dr. Felder, and I know it was my high grade for the semester, but I really think I should get an A in the course because I really worked hard on it and I really understand the material and . . .

---

■ Dear Professor Felder: I am a chemical engineering student at East Indiana Tech. We are using your book, *Elementary Principles of Chemical Processes*, this semester. I think I would learn much better if I could check my solutions against yours. Please send me a solution manual. Sincerely yours, Alvin Wimbish.

P.S. Please send it by Federal Express.

---

■ Um, Dr. Felder—the TA missed this here test page completely on that quiz we took last January and it's got everything right on it—I think I should get full credit.

---

■ Hey, am I speaking to the Chemical Engineering Department at State? . . . Who's this? . . . How you doin', Professor? . . . You don't know me, but my wife got some black crud on our white linoleum floor and the 409 won't get rid of it, and I said, I'll bet you one of them chemical engineering fellers over at State

will know just the thing to clean it up . . . so what should I get, Doc?

---

■ Rich, do me a favor. I just got this manuscript to review from *JPFM* and I'm tied up with a proposal deadline . . . it's right up your alley—Snaveley's latest work on nonnewtonian cheese flow . . . pick up this one for me, ok—I'll owe you. Thanks. Walt.

P.S. By the way, could you get it out by Tuesday?

---

■ Hello, is this Dr. Felder? . . . This is one of your 205 students...I know it's past midnight, but I can't figure out the recycle problem that's due tomorrow and I thought you might . . .

---

■ Dear Professor Felder: We have received the reviews of the paper you submitted in April 1991. All of the reviewers agree that the work is publishable but only after major revisions are made. Reviewer 1 wants you to expand the experimental section considerably, providing details of all the sample preparation steps and adding a glossary of the terms in Figure 6. Reviewer 2 wants the experimental section shortened and Figure 6 replaced with a simple flow chart. Reviewer 3 proposes deleting the experimental section, since everyone knows how to do this sort of measurement, and substituting a *Far Side* cartoon for Figure 6. I agree with the reviewers' suggestions and request that you comply with all of them. Sincerely, E. Wombat, Editor.

P.S. We're trying to clear our inventory of back papers and so I'd like to get the revision back by next Tuesday.

---

■ Hello, is this Dick Felder? . . . Dick, you don't know me but I've got a fantastic opportunity for you to earn big bucks. Let me just have a few minutes of your time to explain . . . □

Research on . . .

# NEURAL NETWORKS, OPTIMIZATION, AND PROCESS CONTROL

DOUGLAS J. COOPER, LUKE E.K. ACHENIE

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Research into the use of artificial neural networks (ANNs) in process control systems has increased dramatically in recent years. Optimization methods play a fundamental role in the training of ANNs as well as in the implementation of modern strategies for multivariable process control. Hence, as illustrated in Figure 1, there is a philosophical relationship among ANNs, optimization, and process control that guides our research program at the University of Connecticut (UConn).

In this article we will present an overview of several research projects that focus on these subject areas. Our goal is to stir the interest and increase the motivation of those students who are considering graduate studies in chemical engineering, and in particular, in neural networks, optimization, and process control.

The research at UConn is conducted in the Intelligent Process Systems Laboratory (IPS Lab), a lab associated with the Department of Chemical Engineering. Both the IPS Lab and the department are located at the UConn campus in Storrs, where about

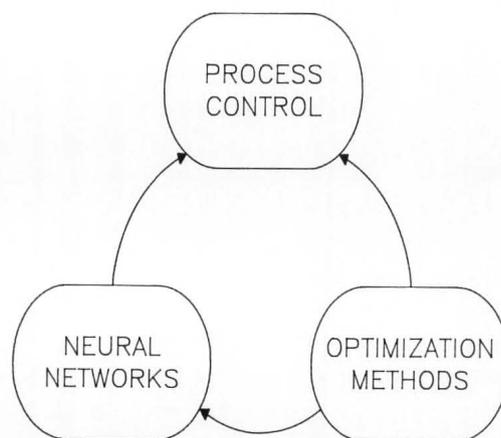


Figure 1. Philosophical relationship guiding research program.

12,500 undergraduates and 3,500 graduate students study under the guidance of some 1,200 faculty members. The Department of Chemical Engineering has about 120 undergraduates, 50 graduate students, and 13 faculty.

The IPS Lab is a relatively new facility that houses researchers and equipment for a number of interdisciplinary projects. A myriad of computer equipment, including RISC-based workstations and the newest personal computers, are available for use by student and faculty researchers. Access to the Cornell Supercomputer Center and high-end computers, such as the Sequent Symmetry S27 parallel computer and IBM vector machines, is possible through high speed networks.

Current projects range from fundamental theoretical studies to applied process implementations and include faculty from chemical, electrical, and mechanical engineering as well as researchers from local industry. The IPS Lab also interacts with other research programs at UConn, including the Biotechnology Center, the Booth Center for Computer Applications Research, the Environmental Research Center, the Institute of Material Science, and the Precision Manufacturing Center.

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**Luke E. K. Achenie** is Assistant Professor of Chemical Engineering and Associate Director of the Intelligent Process Systems Laboratory. He received a BS from MIT in chemical engineering (1981), an MS from Northwestern in engineering science (1982), and an MS in applied math (1984) and a PhD in chemical engineering (1988) from Carnegie Mellon University.

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## CURRENT RESEARCH IN THE IPS LAB

The number and direction of individual research projects are influenced by technological needs of government agencies and industry, as well as developments in science and technology. Some of the research projects currently receiving attention by IPS Lab researchers are discussed in the following paragraphs.

### Neural Network Architectures for Control

ANNs are computing tools made up of many simple, highly interconnected processing elements. ANNs are generating excitement both because they are able to model a wide range of complex and nonlinear problems with relative ease and because they have proven to be powerful and easy-to-implement tools for pattern recognition applications.

ANNs hold additional promise that make them particularly interesting to the process control researcher. For example, ANNs can be used to model complex processes without requiring the engineer to possess a fundamental understanding of the underlying physical phenomena. Further, they can model processes and recognize patterns when the data is imprecise or corrupted with "noise." Finally, ANNs are relatively easy for practitioners to employ in solving real-world problems compared to more traditional statistical and first-principles approaches.

In process control research, investigators have proposed using ANNs for modeling nonlinear process dynamics, for filtering noisy signals, for modeling the actions of human operators, for interpreting advanced sensor data, and for fault detection and diagnosis. Despite these efforts, there are still a number of issues which must be addressed if ANNs are to fulfill their promise in process control applications.

Knowledge is stored in ANNs by the choice of function used in each processing element (or neuron), by the way the neurons are connected to each other, and by the weighting values used in each neuron connection. These choices, taken together, comprise the network architecture. Three architectures receiving attention by researchers include feed forward nets such as the backpropagation ANN shown in Figure 2, recurrent nets such as the single layer Hopfield ANN shown in Figure 3, and vector quantizing nets such as the Kohonen ANN shown in Figure 4.

Each of these architectures has a number of variations. For example, when considering the backpropagation ANN, the number of neurons in the input and output layer is typically determined by the application. However, the number of hidden layers and the number of neurons within each hidden layer must be chosen by the engineer and is often determined by trial-and-error. In one research project, we are employing analysis tools such as singular value decomposition and variational ap-

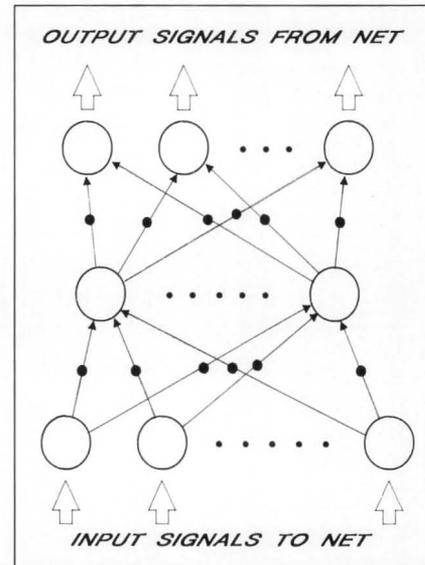


Figure 2. Backpropagation neural network.

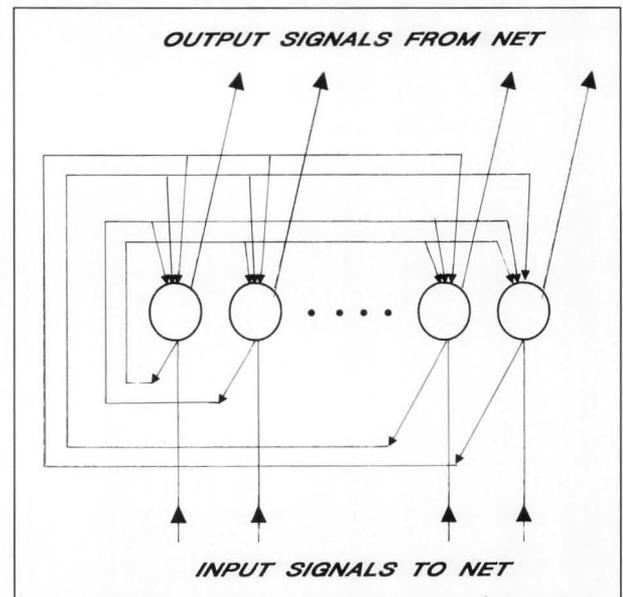


Figure 3. Single layer Hopfield neural network.

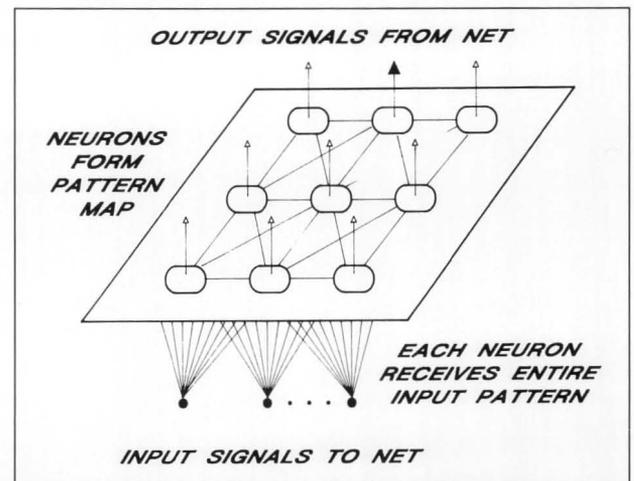


Figure 4. Kohonen neural network.

proaches<sup>[1]</sup> to develop a theoretically sound methodology for determining appropriate net architectures for particular applications.

Once an architecture is chosen, the engineer must make decisions about ANN training. Typically, training data is either historical data from the actual process or simulated data generated from computer models of the process. A network is repeatedly exposed to this data until it "learns by example" as it converges on the process relationships contained in the data.

Thus, the engineer must decide how much training data is adequate, whether this data properly spans the entire range of expected operation, and how much training is required before the ANN can be considered converged. The answers to these and similar questions, especially as they pertain to ANN applications in process control, are also under study at the IPS Lab. In one recent effort,<sup>[2]</sup> we compared the strengths and weaknesses to two ANN architectures when employed for pattern-based adaptive process control.

A current investigation considers the use of faster optimization algorithms such as successive quadratic programming and conjugate gradients coupled with efficient trust region techniques to significantly speed up training times of ANNs. Implementation of these techniques on parallel computers will also be investigated.<sup>[3]</sup>

### Pattern-Based Adaptive Process Control

A controller continually adjusts a process input variable so that the controlled output variable successfully tracks a desired value or set point. A well-tuned controller manipulates the input variable both to minimize the impact of unplanned disturbances and to track any changes in the set point value.

Many chemical processes are nonlinear and/or have a process character which changes with time. A process may have a changing character, for example, due to fouling or catalyst deactivation over time. Hence the tuning of a controller on such processes must be self-adjusting or adaptive if desirable performance is to be maintained.

One approach for making process controllers adaptive is to employ a process model internal to the controller architecture which describes the dynamic be-

havior of the process. If, whenever the process character changes, this model is updated so that it remains descriptive of the current process dynamics, then a wide variety of popular model-based control algorithms such as Internal Model Control or Dynamic Matrix Control can be used to maintain desirable process control performance.

The traditional method for updating the controller process model is through regression of recently sampled process input-output data. The result is a correlative model between the manipulated variable and controlled variable that can be used in many adaptive algorithms. This traditional architecture is illustrated in Figure 5.

In the IPS Lab, a different approach to controller model updating is under study that may ultimately prove easier for industrial practitioners to employ. In this research, the performance of the controller is assessed by evaluating the patterns exhibited in the controller error, which is the difference between the desired set point and the measured value of the controlled variable. The pattern recognition capabilities of a neural network are exploited to perform this analysis and to relate observed patterns to required updates in controller model parameters. A

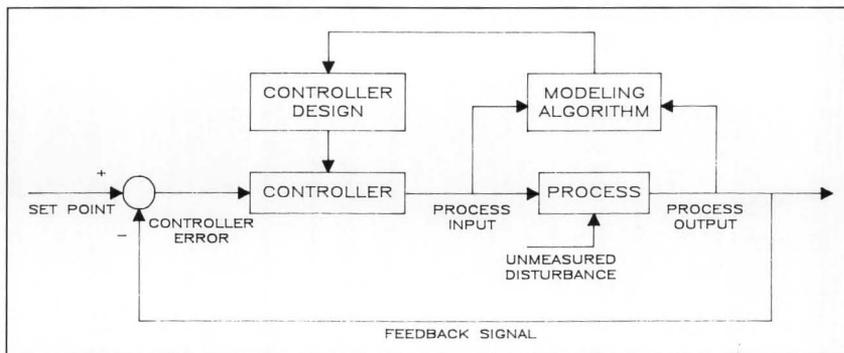


Figure 5. Model-based adaptive process control architecture.

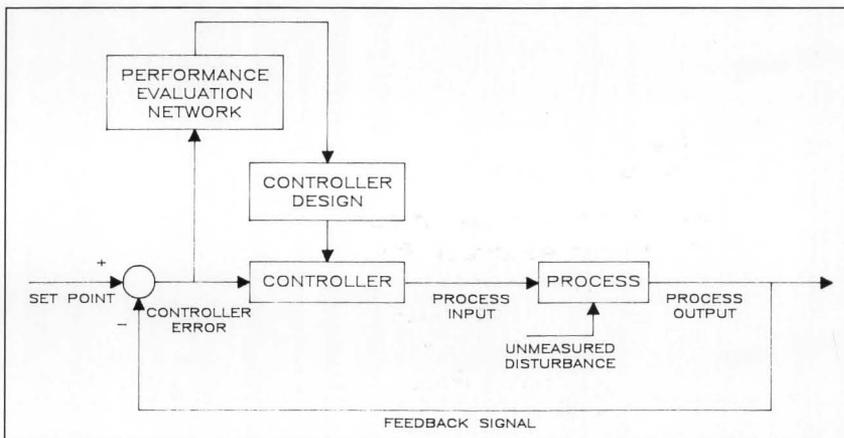


Figure 6. Pattern-based performance feedback adaptive controller.

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***The design of a neural network which can recognize both the oscillatory and non-oscillatory patterns that are associated with aggressive, desirable, and sluggish controller performance is reasonably straightforward.***

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pattern-based performance analysis architecture is illustrated in Figure 6.

Take as an example a process that responds to a set point change with a large overshoot, followed by slowly damping oscillations. One possible explanation is that the gain and/or time constant of the controller model is small relative to that of the actual process. Alternatively, an explanation for a slow response after a set point change is that the gain and/or time constant of the controller model is too large. Hence, the manner in which a poorly performing controller is mistuned can be inferred from the patterns displayed in the recent history of the controller error.

The design of a neural network which can recognize both the oscillatory and non-oscillatory patterns that are associated with aggressive, desirable, and sluggish controller performance is reasonably straightforward. The challenge is to associate these transient patterns with the required updating of the controller model parameters in order to restore desired performance. Methods for achieving this are under study in the IPS Lab, and recent successes are based on approximating all real processes with a generic or "ideal" simulated process.<sup>[2,4,5]</sup>

#### ***Pattern-Based Process Excitation Diagnostics***

The traditional method for updating the process model internal to an adaptive controller (as illustrated in Figure 5) is based on regression of recently sampled process input-output data. To ensure that a properly descriptive process model results from the regression, data samples must be collected when the process is experiencing a meaningful or "sufficiently exciting" dynamic event. During such an event, the changes in the manipulated process input must impart changes to the process output variable that clearly dominate both the measurement noise and any dynamics resulting from unmeasured disturbances.

The engineer often uses simple criteria for excitation, such as when the difference between the model-predicted estimate of the output variable and the actual measurement of that variable exceed some minimum value. Unfortunately, such an approach is not very reliable for detecting when the process is experiencing input-output excitation

and fails altogether when the disturbance dynamics dominate the event.

Thus, we are studying innovative methods for the diagnosis of process excitation that are reliable and easy to use. In this work, we initially focused on patterns exhibited in the process input variable alone under the assumption that if the process input was experiencing significant dynamics, then the process will be sufficiently excited for reliable data regression.<sup>[6]</sup>

Building on this idea, current research exploits the pattern recognition capabilities of ANNs to construct an improved excitation diagnostic tool. The approach under study considers the recent histories of both the input and output sampled data patterns together as a complete process "snapshot." The neural network is being trained to observe the behavior of both variables simultaneously and to signal whenever a dynamic event that is producing process input-output data suitable for model regression is in progress.

#### ***Control Design with Objective Prioritization***

Controller designs based on the use of an internal controller model, such as Dynamic Matrix Control (DMC), are finding their way into industrial practice. One advantage to the DMC architecture is that in many applications, relatively simple process models are adequate to achieve good control performance. Further, DMC can handle soft control constraints in a straightforward and systematic manner.

A multivariable DMC implementation where control objectives are to be balanced against economic objectives may be achieved through the use of weights.<sup>[7]</sup> However, this strategy forces the engineer to specify a large number of weights, which is equivalent to specifying a large number of tuning parameters. The problem is compounded when engineers are responsible for many control loops in a large plant, compelling them to resort to *ad hoc* or trial-and-error tuning.

A method for circumventing this problem is the modular multivariable controller design methodology. In this approach, manipulated variables are designated as primary or secondary, where primary variables are the last to be allowed to achieve a desired optimum level. Unfortunately, in order to

*Continued on page 221.*

*The object of this column is to enhance our readers' collection of interesting and novel problems in chemical engineering. Problems of the type that can be used to motivate the student by presenting a particular principle in class, or in a new light, or that can be assigned as a novel home problem, are requested, as well as those that are more traditional in nature and which elucidate difficult concepts. Please submit them to Professors James O. Wilkes and Mark A. Burns, Chemical Engineering Department, University of Michigan, Ann Arbor, MI 48109-2136.*

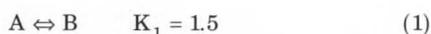
## THE INFLUENCE OF CATALYSTS ON THERMODYNAMIC EQUILIBRIUM

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The influence of heterogeneous catalysts on how chemical equilibrium calculations are carried out is demonstrated by the following short problem, which will be viewed as a simplified representation of methanol synthesis.

### Problem Statement

The inlet feed to a catalytic reactor is pure A. What is the *maximum* mole fraction of B that can be obtained in a catalytic reactor for the parallel, reversible reactions with the indicated equilibrium constants



### Solution

A reasonable approach is to solve the two equilibrium equations simultaneously

$$K_1 = \frac{x_B}{x_A} \quad K_2 = \frac{x_C}{x_A}$$

to obtain the following mole fractions

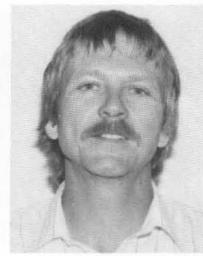
$$x_A = 0.08$$

$$x_B = 0.12$$

$$x_C = 0.80$$

But if the appropriate catalyst was chosen so as to accelerate Reaction (1) preferentially, then a much higher mole fraction of B could be obtained ( $x_B = 0.60$ ). That is, the mole fraction as a function of time would follow a pathway such as that shown

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in Figure 1, and the above mole fractions would only be obtained at long times. To simplify generation of Figure 1, the forward rate constant of Reaction (1) was assumed to be 100 times the forward rate constant of Reaction (2). In an actual catalytic system these rate constants can differ by many more orders of magnitude. If the reactor residence time was chosen in the broad region in Figure 1 where product B is favored, then a much higher concentration of B could be obtained than expected based on consideration of both equilibrium reactions simultaneously. Because of its larger rate constants, Reaction (1) reaches equilibrium so rapidly that it is not affected significantly by Reaction (2) until longer reaction times.

### Discussion

Most undergraduate textbooks in kinetics and reactor design discuss heterogeneous catalysis because the majority of chemical processes use a catalyst to obtain desired products at high rates. Many of these textbooks, however, either do not mention the interaction between catalysts and thermodynamic equilibrium, or they give a false impression of how catalysts affect practical equilibrium obtained in a chemical reactor. For example, typical statements from reactor design textbooks about this topic are<sup>[1-3]</sup>

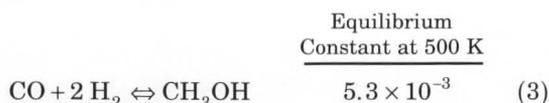
• *The thermodynamic equilibrium is unaltered by the presence*

of a catalyst.

- A catalyst changes only the rate of reaction; it does not effect the equilibrium.
- The position of equilibrium in a reversible reaction is not changed by the presence of a catalyst.
- Equilibrium conversion is not altered by catalysis.

These statements are all correct, but they may give the wrong impression because they only apply at times that may be long compared to the reactor residence time. They do not indicate that catalysts give us the option of deciding which reactions to consider in the equilibrium calculations.

Methanol synthesis from CO and H<sub>2</sub> clearly demonstrates this point. Consider the two reactions



At first glance, it would not appear worthwhile to build a methanol synthesis reactor; indeed, an ideal equilibrium calculation<sup>[4]</sup> at 20 atm and 500 K for a 1:1 feed composition yields the following mole fractions:

$$x_{\text{CO}} = 0.50$$

$$x_{\text{H}_2} = 6 \times 10^{-3}$$

$x_{\text{CH}_3\text{OH}} = 4 \times 10^{-5}$

$$x_{\text{C}_2\text{H}_5\text{OH}} = 0.25$$

$$x_{\text{H}_2\text{O}} = 0.25$$

For this feed composition, the equilibrium calculation indicates that H<sub>2</sub> is almost completely consumed and the main products are ethanol and water. **Almost no** CH<sub>3</sub>OH is predicted to form based on thermodynamic equilibrium for these two reactions. Of course, commercial plants exist that make methanol on a large scale from CO and H<sub>2</sub>, and the undesired reactions are the formation of C<sub>2</sub>H<sub>5</sub>OH and hydrocarbons.

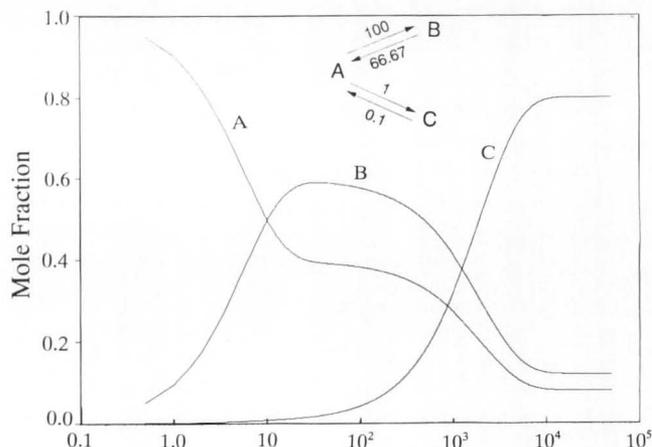
If only Reaction (3) is considered in the equilibrium calculation, however, then a reasonable yield of CH<sub>3</sub>OH is predicted:

$$x_{\text{CO}} = 0.50$$

$$x_{\text{H}_2} = 0.36$$

$x_{\text{CH}_3\text{OH}} = 0.14$

In this case, only a fraction of the H<sub>2</sub> is consumed. Clearly this is the correct equilibrium calculation for the industrial process; **even though** C<sub>2</sub>H<sub>5</sub>OH **also forms**,<sup>[5,6]</sup> we do not consider Reaction (4) in the equilibrium calculation because Reaction (3) is so



**Figure 1.** Mole fractions of A,B,C versus reaction time for the parallel, reversible decomposition of A to form B and C. Rate constants in inverse minutes are indicated for first-order reactions.

much faster. If we did, we would conclude that the measured methanol conversion is significantly higher than the equilibrium conversion. The formation of CH<sub>3</sub>OH from CO and H<sub>2</sub> follows the same type pathway as shown for component B in Figure 1, except that the equilibrium constants differ by almost four orders of magnitude for Reactions (3) and (4) instead of one order of magnitude for Reactions (1) and (2).

The interaction between catalysis and thermodynamics was discussed by Hamilton and Greenwald,<sup>[7]</sup> but their ideas are not addressed in most of the reactor kinetics or thermodynamics textbooks; only a few textbooks on heterogeneous catalysis discuss the influence of thermodynamic equilibrium.<sup>[8]</sup> Hamilton and Greenwald distinguished between true equilibrium (infinite time) and practical equilibrium. Indeed, if the methanol synthesis reaction is run for extremely long contact times, then almost no CH<sub>3</sub>OH remains.<sup>[6]</sup> Hamilton and Greenwald emphasized that the catalyst constrains possible reaction pathways so that the uncatalyzed reaction is essentially forbidden. Thus, the minimum Gibbs free energy is not obtained; instead the minimum along a highly constrained path is obtained.

As pointed out by Satterfield,<sup>[8]</sup> a selective catalyst directs one reaction essentially to completion while having little or no effect on other reactions. Thus, the most stable products are not formed. What the reaction to synthesize methanol from synthesis gas shows is that in calculating equilibrium conversion, we must consider the two reactions separately because the rates of reaction differ significantly. That is, the Gibbs free energy is not minimized for the system; instead, each equilibrium calculation is done independently of the other. For our example, this

means that the maximum mole fraction for  $\text{CH}_3\text{OH}$  is 0.14, not  $4 \times 10^{-5}$ .

Thus, catalysts can modify practical thermodynamic equilibrium by dictating that equilibrium for each reaction be considered separately. Catalysts do not change *equilibrium constants*, but the properly chosen catalyst allows us to ignore many of the reactions in equilibrium calculations because their rates are low. As pointed out by Hamilton and Greenwald<sup>[7]</sup>

*Of all the compounds that might theoretically form, it is well known that it is necessary to have thermodynamic information on only  $\text{CO}$ ,  $\text{H}_2$ , and  $\text{CH}_3\text{OH}$  to calculate equilibrium concentrations and yields in such a selectively catalyzed system.*

We ignore an entire class of reactions when we calculate the equilibrium yield for methanol without also considering the equilibrium for paraffins formation, even though  $\Delta G > 0$  for methanol formation, and  $\Delta G < 0$  for methane and higher paraffin formation. All the higher alcohols and all the paraffins are more thermodynamically favored than methanol,<sup>[9]</sup> but they are formed in very low concentrations over the typical  $\text{ZnO/Cr}_2\text{O}_3$  catalyst.

In summary, catalysts affect practical equilibrium

conversions because conversions much higher than those calculated from equilibrium can be obtained in catalytic reactors.

## ACKNOWLEDGMENTS

I wish to thank Prof. William B. Krantz for very fruitful discussions about this topic and Prof. Scott H. Fogler for some useful suggestions. Thanks also to Eric M. Cordi for generating Figure 1.

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## ChE book review

### INTRODUCTION TO MACROMOLECULAR SCIENCE

by Peter Munk

John Wiley and Sons, Inc., New York; 522 pages,  
\$44.95 (1989)

Reviewed by  
Matthew Tirrell  
University of Minnesota

As a research field, polymer science has flourished within chemical engineering more than in any other traditional academic discipline and, while I have not surveyed this quantitatively, I feel confident in asserting that many more courses on aspects of polymer science and technology are taught in chemical engineering than in any other kind of department. That fact alone makes the appearance of a new textbook on polymer science a noteworthy event for chemical engineering. On top of that, there is the fact that polymer science has become so broad a topic that there are many ways to approach its presentation and concomitant, there is a general dissatisfaction with the books available for instruction during the last five years. It was precisely this feeling that led Professor Munk to write this book, as he explains in the Preface; for this, I salute him, since complaining is certainly easier and more immedi-

ately gratifying than bookwriting.

The book is intended for a first course in polymer science but is at a level that would be appropriate for introducing the subject to either seniors or graduate students. It comprises five chapters, the first four of them quite large and broad in themselves: Structure of Macromolecules, Techniques for Synthesis of Polymers, Macromolecules in Solution, and Bulk Polymers. These are solid, information-rich chapters. The fifth chapter, Technology of Polymeric Materials, is but ten pages long and is not really up to the job announced by its title.

The flow of topics, beginning with a detailed discussion of the ways that macromolecules can be put together, followed by a second detailed chapter on synthetic methods is, in my view, exactly appropriate for an introductory book. Connections made between uncharged, synthetic polymers, which are the main subject of the book, and important related topics, such as polyelectrolytes, micelles, proteins, and polynucleotides, are very well done and useful. Particular care has gone into placing polymer science in a proper context, which is both educational for the reader and likely to stimulate student interest by helping them see connections.

The third chapter on polymers in solution is also filled with important and useful information on the basic physical chemistry of mixture of polymers with solvents. I begin to find divergence between the

author's point of view and mine in the heart of this chapter. The presentation of experimental methods, when viewed from the perspective of current practice, overemphasizes membrane osmometry and ultracentrifugation and underemphasizes scattering of light and, particularly, of neutrons. Neutron scattering goes unmentioned in this chapter on solutions and only makes a brief appearance in the fourth chapter on bulk polymers. The section on equation-of-state solution theories misses a great opportunity to highlight the work of Professor Munk's colleague in chemical engineering, Isaac Sanchez who, with Bob Lacombe, showed (in the late seventies) how the Flory-Huggins lattice model could be extended in a simple but powerful way to comprehend PVT effects in the phase behavior of polymer mixtures. Nonetheless, this is a perfectly usable chapter by any instructor of polymer science, no matter what his or her personal prejudice might be.

Up to this point, this book ranks, in my estimation, with Paul Flory's first book, *Principles of Polymer Chemistry*, in terms of the sequence and balance of coverage. (I should add, so that you can calibrate me and my judgment, that I insist that any new graduate student working with me become completely conversant with the entirety of Flory.)

The gap of Professor Munk's divergence from my ideal path widens in Chapter 4 on bulk polymers. I suspect that this is related to a divergence from Professor Munk's own interests, as he is a widely respected physical chemist with interests in polymer solutions. Chapter 4 still contains considerable useful information, and most of what is in it is important. However, it is the omissions to which I object. Perhaps the single most important development in bulk polymers during the eighties has been the elaboration of the concept of reptation. This word is mentioned exactly once in this book. Rubber elasticity, classical viscoelasticity of polymers, and mechanical properties of semicrystalline polymers are all well covered in this book, making it very suitable for a course that deals significantly with physical properties of polymers. On the other hand, modern polymer melt rheology is essentially absent.

Another point of omission in this book (with which I disagree, but which is done explicitly and intentionally by the author) is the absence of primary references. No references are given in the text (except for figure captions); references, to other books exclusively, are given in lists for all chapters at the end of the book. I don't mind the collection of all references at the end, or even the lack of references inserted in the text—but I think it is a mistake not to tell students where the primary literature is. They

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### UNIVERSITY OF FLORIDA

A tenure-track Assistant or Associate Professor position is available for August 1993 at the University of Florida. PhD degree required in Chemical Engineering or related field. The preferred research area is biochemical engineering; however, outstanding candidates in any area will be considered. Job duties include teaching undergraduate and graduate courses, developing and conducting sponsored and unsponsored research, supervising and directing the educational and research programs of graduate students, and participating in departmental, college, and university affairs. Applicants should submit a brief resume, a description of research objectives, and the names of three references to: Faculty Search Committee, Department of Chemical Engineering, University of Florida, Gainesville, FL 32611. The deadline is 12/31/92. The University of Florida is an Equal Opportunity/Affirmative Action Employer.

miss seeing the origins of textbook facts, complete with all the experimental considerations, errors, etc. Without that exposure, some students develop either an unwarranted reverence, or an insufficient appreciation, for the achievement behind what they read in their textbooks.

On balance, this is a very good, solid, usable textbook for many variations on polymer science and engineering courses likely to be taught in chemical engineering departments. I have used it for the last year to introduce new graduate students to the research field. As mentioned earlier, complaining about books is a favorite pastime among instructors of polymer science. Professor Munk's book should diminish the complaints and raise the standard for those who would aspire to do better. □

# CHEMICAL REACTION ENGINEERING

## *A Story of Continuing Fascination*

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Iowa State University  
Ames, IA 50011

Chemical engineering in its most general sense is broadly centered on two aspects of chemical processing: transformation engineering and separation engineering. Transformation engineering addresses the engineering of physical and chemical change, while separation engineering deals with the principles and tools by which the products of transformation can be obtained at stated levels of purity.

The engineering of chemical change constitutes the core of chemical reaction engineering. Given the centrality of chemical change in any chemical process, it is surprising that the principles and practices of chemical change did not coalesce into a well-defined area until the late 1950s. It was called "applied kinetics" before that time. Part 3 of *Chemical Process Principles*, by Hougen and Watson,<sup>[1]</sup> was perhaps the first book to attempt a coherent educational presentation of the principles of reactor design.

The subsequent development of chemical reaction engineering (CRE) was rapid, almost dramatic, in the 1960s and 1970s. The increasing use of sophisticated methods, so aptly and appropriately discussed by Aris,<sup>[2]</sup> provides a reflective backdrop to the continuing research in this area. The field has expanded so vastly and so heterogeneously, through the export of its basic theme (interaction between chemical and physical factors) to other areas of chemical transformation, that its own scope—if one can conceive of a scope for this "moving boundary problem"—is now being increasingly linked ("confined" is not the right word) to chemical and petrochemical processes. Among these are biochemical reaction engineering, microelectronic reaction engineering, polymer reaction engineering, and electrochemical reaction engineering.

In the author's opinion, this is an irreversible change (perhaps in the right direction), and chemical reaction engineering will continue to grow vertically within its own province, but always overlapping interactively with the boundaries of its progeny. In any case, considering the quick dispersal of knowledge that is evident today and the commonality of many prin-

ciples, one can only conceive of different *disciplines* of CRE. The areas mentioned above are precisely that. If all of them are to come under a single umbrella, then CRE, already interdisciplinary, would be truly ubiquitous.

Over the years, chemical reaction engineering has progressed along two rather different paths. In Europe the emphasis has been more on the application of new and exciting concepts to conventional technologies, including the "bread and butter" conventions. On the other hand, in the United States conventional technologies have not normally held much attraction for academia, except perhaps in some areas such as catalysis. There is much to be said in favor of both approaches, but what is likely to emerge as we move into the 21st Century is a balanced synthesis of the two paths.

### UNDERGRADUATE PROGRAMS IN CRE

Concepts of CRE are taught in different courses. The emphasis in undergraduate curricula usually tends to be on homogeneous reactions, catalytic reactions, and occasionally on multiphase reactions involving two or more reactive phases. It is important that students get a broad exposure to various areas and systems covered by CRE in the junior year—in addition to a more rigorous course involving a few selected systems (depending on the interest and expertise of the instructor). It is not uncommon in today's world to find a graduating student who has had little or no exposure to the emerging areas of a subject, including CRE. This is a situation that must be addressed immediately. Students must be given a firmer grounding in order to cope with the challenges of the next century.



L. K. Doraiswamy received his BS from Madras University and his MS and PhD from the University of Wisconsin. He is presently the Herbert L. Stiles professor at Iowa State University, where he came after retiring as director of India's National Chemical Laboratory. His research has spanned several areas of chemical reaction engineering: gas-solid (catalytic and noncatalytic) reactions, stochastic analysis, and surface science approach to catalytic reactor design.

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Another concept that should be implemented is a scaled-down version of the think-tank concept in which the student is given a design problem and makes no *a priori* assumption as to the type of reactor to be used. This is beautifully brought out in a Danckwerts Memorial Lecture by O. Levenspiel<sup>[3]</sup> where he illustrates the concept with a specific example. This approach stimulates thinking and analysis, and every effort should be made to provide a course, or some kind of an individualized or tutorial mechanism, to foster an "educational think tank" of the type proposed.

### **COMPLEMENTARY ROLES OF ANALYSIS AND APPLICATION**

All too often, at the end of a course the student has learned most of the principles but has no clue as to the systems (existing or potential) where they might be used. Sharma and Doraiswamy<sup>[4]</sup> addressed this problem in their book, where many examples are given which illustrate principles or design situations. Furthermore, the student should acquire a feel for numbers, *e.g.*, What is a "slow" reaction? What is the range of effective thermal conductivities of common catalysts? What is the range of liquid-side mass transfer coefficients in some real systems? The argument that these concepts can be acquired later is moot and less than comforting.

This brings us to the pedagogic problem of analysis vs. application. Many books, including Bird, Stewart, and Lightfoot's *Transport Phenomena*,<sup>[5]</sup> tend to be analysis oriented. There is great merit in that approach—it was certainly the correct approach at a time when there was an overdose of empiricism and when descriptive and "experience" aspects of process technology held sway. But it is increasingly evident that analysis and application must complement each other. In CRE courses, for example, one can talk of controlling regimes and can present detailed analytical methods for discerning the controlling regimes, but it should be supplemented with industrial (or even laboratory) examples of reactions conforming to those regimes. Thus, if one is considering the mass transfer regime, it would be instructive to illustrate with examples such as dehydrogenation of cyclohexane, decomposition of hydrogen peroxide, and hydrogenation of phenol (to name a few).

It should also be mentioned that a regular graduate course in CRE should involve a problem where the student is required to design a reactor for a selected reaction, starting from the base level—a literature search for getting the correct rate equation. (This is slightly different from Levenspiel's concept where the reaction is new and no information is available.) Rase's *Chemical Reactor Design for Process Plants*<sup>[6]</sup> contains such examples in its second volume. In today's context, however, these examples should have a higher content of analysis and modeling.

### **MORE CHEMISTRY IN CRE**

And—let's face it—the basis of all chemical engineering is, after all, chemistry, and the average chemical engineering student's knowledge of chemistry is less than it should be. Either during a course in CRE or by additional coursework in chemistry, students must be required to gain a firmer feel for chemistry—definitely for inorganic and organic chemistry, and biochemistry and polymer chemistry in special cases. Here, students of biochemical engineering or polymer reaction engineering are at an advantage since they enjoy greater exposure to the chemistry aspects of the subject than do students in a regular CRE course in chemical engineering. Such exposure at an early stage enhances the student's ability not only to deal with everyday problems subsequently encountered on the job, but also in later years to formulate exciting problems of current or potential relevance. The need for more chemistry in chemical engineering was stressed by the author in a lecture (delivered at Wisconsin some years ago<sup>[7]</sup>) which included a number of examples to strengthen the argument.

### **SOME RESEARCH AREAS**

In a field that covers such a large mix of possibilities, it would be presumptuous to list areas for continued or future attention. Even so, there are certain areas which have the potential for significant impact on the chemical industry (used in its broadest sense). The following suggestions are perceptions not uncolored by the author's personal fancy or evaluation, and should therefore be viewed in that light.

#### ***Catalysis and Catalytic Reaction Engineering***

In an age where there is an increasing tendency to

frown on conventional topics, catalysis is a refreshing exception. It is among the oldest areas in chemistry, and yet it continues to be new. Perhaps its main driving forces are the omnipotence of catalysis and the intriguing fact that, in spite of its long run, it is just beginning to emerge from the shadows of empiricism. We are still a long way from answering the question "Can one design a catalyst for a given requirement?"—this could be the main reason for the unrelenting research in this area. With the help of sophisticated instruments, we are now looking at catalysis at its most fundamental level, particularly with the objectives of identifying the participating sites, mapping their energy levels, and understanding the basis of selectivity. Iowa State University has a strong school of research in these areas.

From the point of view of catalytic reaction engineering and starting with the early publications of Amundson,<sup>[8]</sup> we seem to have almost reached the end of the line where steady-state analysis is concerned, and the state-of-the-art has been fully covered by Aris<sup>[9]</sup> (also see Levenspiel<sup>[10]</sup> and Froment and Bischoff<sup>[11]</sup>). That is not so, however, with respect to unsteady state analysis (including multiplicity), for which some new mathematical tools have been developed.<sup>[12]</sup> The role of adsorption and the use of nonideal isotherms has all but evaded the attention of reaction engineers, and only recently have we started to look at adsorption, catalysis, and reactor design in their totality.<sup>[13]</sup> This is presently an active area of research at Iowa State University, and a recent conference in Poland addressed the problem, perhaps for the first time in an international forum. Another approach that is gaining ground in catalytic processes is the simultaneous consideration of feedstock, catalyst, reactor, selectivity, and separation. I believe that these trends will continue well into the 21st Century.

An area of catalytic reactor design that will gain momentum is gas phase polymerization in fluidized bed reactors. Following the first flush of success of fluidized beds in the petroleum and petrochemical industries, interest in the area waned when it was found that fluidization was no panacea for reactor evils. It began to wax again when coal conversion processes revived attention—but with a difference: fluidization of large particles. Perhaps the stage is now set for another revival—in the area of polymerization.

In addition to heterogeneous catalysis, we have homogeneous catalysis, where innovative coordination chemistry and catalyst recovery play vital roles. An exciting example is reductive carbonylation of

methanol. It is here that early exposure to inorganic chemistry would be most useful. It would also be useful in catalyst preparation technology, and it is in this area that our ignorance coefficient is woefully high. Impregnation and drying of catalysts are still almost entirely empirical operations. The analysis of Varma and collaborators in a series of ten papers (see, for example, Part 9 which contains all previous references<sup>[14]</sup> and Part 10, to appear soon) shows that an optimum catalyst profile in the pellet can increase catalyst activity and selectivity in many reactions. This underscores the need for a more rigorous espousal of catalyst manufacturing science.

### ***Solid State Reaction Engineering***

Today, research in solid state materials is a frontier of enquiry. Solid-solid reactions were first mentioned in the mid-80s<sup>[4]</sup> as an area of interest in chemical reaction engineering. With the increasing participation of chemical engineers in materials development, this interest has grown to an astonishing level today. Materials of interest include structural composites, ceramic materials, new metal compositions, and microelectronic materials. The engineering science analysis of the reactions involved in these preparations has been late in coming, but it now appears to have taken root. There is little doubt that this interest will rise exponentially in the years ahead. Take microelectronics as an example of the role of CRE in these materials; here we have processes such as deposition, etching, diffusion, and implantation, in which different types of reactors are employed to carry out both homogeneous and heterogeneous reactions. CRE inputs are just beginning to flow into the analysis of these operations. There is a need to introduce electronic materials concepts at the undergraduate level, perhaps as an elective.

Plasma-enhanced chemical vapor deposition using a variety of techniques is an important method of preparing solid state materials, particularly catalytic materials. A strong school of research as Iowa State University is exploring the preparation, characterization, and use of such materials.

### ***Reaction-Cum-Separation (or the reactor-separator combo)***

One way to cut capital costs (and increase conversion and selectivity in some cases) is to carry out the reaction and separation steps in a single piece of equipment, or to devise technologies where useful side-products are formed. The earliest example of the first kind is the well-known Solvay tower in which a number of operations occur simultaneously

to ultimately produce soda ash. Indeed, the Solvay tower is a veritable combo of multiple operations. Although this reactor combo is no longer a complete black box, many aspects of it still are. But that is only one major example. A number of other, less complicated, examples of reaction-cum-recovery can be cited: the removal/recovery of acid gases such as CO<sub>2</sub>, H<sub>2</sub>S, SO<sub>2</sub>, recovery of valuable products from waste or dilute streams, or reaction-cum-crystallization in the manufacture of such important products as citric and adipic acids.

There is increasing interest, particularly in schools outside the United States, in the analysis of combo reactors. The type of research involved here is usually concerned with the application of new and innovative ideas in the so-called conventional manufacturing processes. At Iowa State, research in crystallization has been in progress since the 1950s, and more recently the problem of reaction-cum-crystallization has been added to this continuing program.

In the removal of oxygen present in levels below 2% in gases like CO<sub>2</sub>, it would be desirable to develop absorbents with the ability to mimic hemoglobin-type regenerative action. Some manganese compounds probably have such an ability. In the separation of *p*- and *m*-xylenes the difference in reactivity of the two can be successfully exploited. Thus, one can selectively alkylate *m*-xylene (with the *para* isomer untouched) using acetaldehyde to give dixylyethane (DXE).<sup>[15]</sup> DXE, when cracked, gives half the amount of the *meta* isomer back along with the industrially useful side-product dimethylstyrene. Innumerable other instances can be quoted involving reactive extraction, dissociation extraction reaction, and dissociation extraction crystallization to buttress the contention that this is indeed an exciting area of research with unlimited scope for the use of novel concepts.

This area of research can serve as an example to strengthen the point made earlier that there should be more chemistry in CRE education and research. In a lecture the author heard some years ago, the point was made that many companies do not expect significant chemistry input from chemical engineers. It would seem that chemistry input of the kind mentioned here must come primarily from reaction engineers exposed to a lot of chemistry. (Here, chemistry means the chemistry of relatively large and complex molecules encountered in, say, drugs and pesticides manufacture.) It is significant that one sees a greater degree of chemistry orientation in biotechnology and polymer science and engineering.

### **Microphase Reaction Engineering**

Reaction of a component from a liquid phase (which we will call Phase 1) with another reactant of limited solubility diffusing from a second phase can be hastened if a small quantity of a microphase can be added to the system. If the particle size of the microphase is smaller than the diffusion scale of the reactant, then these particles can get inside the liquid film and transport more of the reactant from Phase 2 into Phase 1. From two excellent reviews on the subject,<sup>[16,17]</sup> it seems clear that the use of a microphase (which may be a simple adsorbent like active carbon, a catalyst, or a liquid dispersed as a colloid) can in some cases enhance the reaction rate by almost an order of magnitude.

Extension of this concept to include (1) sparingly soluble solute in Phase 1 itself, (2) a precipitated product with particles small enough to enter the liquid film (or the fluid element in the language of the penetration theory), capture more of the reactant from the neighborhood of the second phase and discharge it into the bulk of Phase 1, and (3) micellar catalysis, has shown interesting possibilities. Particularly in cases like the production of citric acid (where each of the two major steps involved contains a precipitating product phase), control of conditions to reduce particle size to microphase levels can lead to remarkable enhancements in the precipitation rate. This is obviously a kind of precipitate-induced autocatalysis and offers much challenge both for the theoretician and the experimentalist.

### **Organic Synthesis Engineering (selectivity engineering?)**

Much of the progress in CRE has been in areas relating to the production of high tonnage chemicals. It is only in the last ten to fifteen years that another focus has emerged: reaction engineering of small volume chemicals. It is surprising that most of the hundreds of reactions involved in organic synthesis have remained outside the pale of CRE. Indeed, one is hard put to think of more than a few important organic name reactions that have been subjected to rigorous analysis. Examples are: Henkel reaction by Doraiswamy and collaborators,<sup>[18,19]</sup> Grignard reagent preparation by Hammerschmidt and Richarz,<sup>[20]</sup> and Kolbe-Schmitt reaction by Phadtare and Doraiswamy.<sup>[21]</sup>

With the increasing importance of small-volume chemicals, particularly in the field of drugs and drug intermediates, one would be greatly surprised if reaction engineers do not, almost as a natural course, extend their domain to include this area as a formal

part of CRE research. One sees considerable activity in Europe (particularly in Bourne's school) and in some industrial research and development centers in Europe and the USA, but a more pronounced involvement of CRE groups in academia is desirable.

Several ways of improving selectivity have been used by chemists,<sup>[22]</sup> some of which are being pursued vigorously by chemical engineers. Phase transfer catalysis is an outstanding example of the former in which some reaction engineering groups are evincing keen interest. Other means of increasing selectivity are through the use of micelles, microphases, catalysts like zeolites and molecularly engineered layered structures, and controlled levels of micromixing. The last is particularly attractive from an engineering science point of view, as attested to by the extensive publications of Bourne and collaborators (for example, Baldyga and Bourne<sup>[23]</sup>). Another rewarding line of approach is the use of ultrasonics. The finding by Luche and Damiero<sup>[24]</sup> that ultrasonification can enhance yields in the Barbier reaction augers well for the increasing role of ultrasonics in synthesis engineering.

A field of research in organic synthesis with great potential for enhanced selectivity and ease of operation is the possibility of extending the concept of supported liquid-phase catalysts to include supported reagents—with all the attendant advantages. The edited book of Hodge and Sherrington<sup>[25]</sup> provides clear evidence of the favorable role of the solid support. With the extensive knowledge we now have of fluid-solid (catalytic and noncatalytic) reactions, this field offers great scope for innovative approaches to, among other things, the reaction-diffusion problems inherent in such systems. Use of photochemistry and enzymes in organic synthesis can also greatly enhance specificity. These are well-known areas to the chemist and biochemist, but there is a definite need for increased CRE input.

#### Other Areas

There are many other areas that merit attention and where there is bound to be continuing interest. Among these are

- interfacial engineering, an area that covers a multitude of systems, including catalysis, colloids, and micellar action
- multiphase reactions (which involve at least one liquid phase) extensively used in the manufacture of fine chemicals
- gas-solid noncatalytic reactions, so common in pollution abatement, preservation of monuments, ore processing, and catalyst regeneration
- analysis of operation "at the edge" in solid cata-

lyzed reactions, meaning operating under conditions where the diffusion and kinetic effects are balanced to maximum advantage

- increased attention to forced cycling
- use of appropriate solvents (for liquid phase reactions) such as dimethylsulfoxide to increase reactivity
- use of ion exchange resins to replace liquid phase acid/base catalysts
- control strategies in multistep synthesis of pharmaceuticals (including computerized optimization of the synthetic route)
- use of aqueous-aqueous extraction in reactive separation
- reaction-cum-separation strategies for recovery of valuable products from dilute solutions, or removal of polluting components therefrom
- hazard analysis and prevention

Many of the areas listed are not "new topics," but certainly all of them thrive on the use of innovative concepts. Areas such as recovery of valuable products from dilute solutions are replete with examples of the use of reaction as a tool for separation and recovery. A general strategy of intensification in which isolated studies have been reported, and which has the potential for treatment as an area of research, is the role of dilution in process technology. An attempt was made by the author some years ago<sup>[7]</sup> to put together the various aspects of intensification by dilution, *i.e.*, dilution of the gas and solid phases in catalytic reactions, dilution of solid in gas-solid reactions, and "natural intensification" due to dilution in biological systems. Increased effort in this area could be very rewarding.

#### CONCLUSION

Education in CRE must explore new possibilities, some of which have been described in this article. Among these are a mini think-tank, a broad exposure to the reaction engineering of a variety of systems to supplement the prevailing practice of enlarging on a few, and initiation of electives in some emerging areas such as solid-state reaction engineering and interface engineering.

The overview presented here with respect to research is indicative of the areas of present/potential relevance. The element of challenge will continue, whether the areas are new or traditional. While the researcher in CRE, like his counterparts in many other areas, must continue to vigorously explore new and emerging fields, let us not throw the conventional areas overboard. Recovery of value-added products from dilute solutions (or waste

streams) is an outstanding example of applying new concepts to old problems. Whether or not they attract one's fancy, their importance will continue undiminished. So the educator, the researcher, and the funding agencies must look at new concepts in traditional areas with almost the same enthusiasm as at the emerging areas. Nucleation and growth must remain simultaneous.

The chemical industry, notwithstanding the strains and vicissitudes imposed by a fluctuating economy and an increasing appreciation of environmental concerns, permeates practically every facet of our lives and depends for its continued development on invention as well as innovation. Invention is getting a novel idea which works; innovation is overcoming all hurdles to its economic use.<sup>[26]</sup> There is scope for both in CRE. To ensure continued dominance, academic research must become increasingly bold, industrial research must be supported rather than managed, and both must be more accommodative of shifts in approach and the delays they entail.

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## REVIEW: Design Project

*Continued from page 174.*

ever, the authors do provide some insight into hazardous operations analysis and general safety considerations.

The nitric acid process selected is the traditional one without the more modern modification of reaction gas compression. Surprisingly little is said about the need for cleanup of the tail gases from the absorber. The authors have provided a relatively simple process with a great deal of supporting data. This should have appeal to faculty members who understand quite well that it is an onerous chore to dig up all the supporting information for a realistic case study.

The use of this text in the design course should follow an introductory design course which treats such matters as equipment cost estimating, profitability studies, profit and loss statements, and the like. The authors point this out in the introductory material. If only one semester is allocated to design, it is the opinion of this reviewer that adoption of this book would be a mistake. On the other hand, if a second semester (or quarter) is available, material in the book can support one or more worthwhile case study projects. □

# A PILOT GRADUATE-RECRUITING PROGRAM

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**D**orothy and John are two outstanding seniors who are beginning to anticipate graduation. Dorothy has worked in a chemical engineering summer job with a company that is eager to have her take a permanent position, while John has worked summers helping professors in various research projects in his department. Both students are vital learners and want to investigate graduate school as a career option.

As they look through graduate school ads and brochures, talk to other students and professors, and read the fall issue of this journal, Dorothy and John begin to generate a list of candidate schools. They notice several marked differences in regard to research emphasis, size of programs, and location, but they are particularly interested in the differences in graduate stipends. Although it appears that the funding differential is less than 10% for the best candidate schools, small discrepancies become significant when their own current budgets are considered.

In early fall both students mail "inquiry forms" to various graduate schools, and a few weeks later they begin to receive the requested information/application packets. By October or November they have submitted several applications (limited somewhat by their student budgets of time and money). Of course, since neither Dorothy nor John want to restrict their other options, they also interview several companies that come to campus. They are interested to note that industrial salaries are a factor of three greater than academic stipends, and that some in-

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*As they look through graduate school ads and brochures . . . [the seniors] begin to generate a list of candidate schools. They notice several marked differences in regard to research emphasis, size of programs, and location . . .*

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**Ron Miller** obtained his BS and MS at the University of Wyoming and his PhD from the Colorado School of Mines, all in chemical engineering. He is currently associate professor on the CSM faculty, where he has taught since 1986.

interviewers discourage participation in graduate work.

The company interviews go well, and both students are subsequently invited for several site visits, at which time challenging and exciting work is displayed. The companies are quite aggressive in their personal contacts. In fact, Dorothy is contacted every month or so by her former summer supervisor for a friendly chat, during which they discuss Dorothy's future plans. In late November, while they are waiting for the first personal contact from a university, both students are being pressed for positive answers to job offers from several companies.

Dorothy, under some pressure for financial security from her family, accepts an offer from a mid-western biochemical firm, and in her natural excitement she tells her friends of her decision. When she subsequently receives a call from Professor Jones of Whatsamatta U. about an interesting research project, she feels she cannot change her mind concerning the industrial position without embarrassment before her peers. The graduate school option is closed in her mind.

John, however, has not applied to the same graduate schools as Dorothy. One graduate school has sent him a video tape of their program, along with

their application packet. A few weeks later the mail brings a follow-up letter and a research summary from the school, inquiring if he has received the packet and requesting the completion of a card that ranks his interests in various research projects.

Because John seems to be an excellent candidate, the department continues to communicate with him about every three weeks. Faculty members (including the department head) call John several times to express their interest in his application. A department administrative assistant, who seems genuinely interested in John's application, serves as the focal point for all written communications. In each letter John receives from the department, he is asked to return some kind of information (in a postpaid envelope) which then provides the department with a progressive exploration of his personal interest in graduate school. With this kind of communication, John keeps the possibility of graduate school alive, though he makes no definite commitments either to industry or academia.

In December the department extends an invitation for John to visit the campus in January, at the school's expense. When John's plane arrives on Thursday evening, he is met by Dr. Chehead, the department head, who takes him directly to a bed-and-breakfast lodging on the edge of campus. Friday is spent in taking departmental tours and in discussions with faculty. Then John's faculty host takes him to dinner on Friday evening, and they discuss all the possibilities and questions raised during the day. John spends Saturday skiing with prospective colleagues who are already graduate students in the department, and a pizza dinner completes an exhausting, but fun-filled, day. Early Sunday morning, Dr. Chehead takes John to the airport for his return flight.

A week later a letter of admission and a stipend offer is sent to John, preceded by a call from Dr. Chehead telling him that the faculty was impressed with his potential. Another faculty, Dr. Egghead, also calls John to discuss concepts in reprints which interested him during his visit. After deliberating for another week, John formally accepts the department's offer and tells friends of his decision.

## PLANNING REVISIONS TO GRADUATE RECRUITING

The above composite case studies of Dorothy and John emphasize recent applicant contact changes in our graduate recruiting program at the Colorado School of Mines. Our program objectives were to increase the number and quality of accepted appli-

cants to both our traditional program and to a new non-thesis MS program for industrial engineers in the Denver area. Our target population was students with a traditional or a non-traditional background allied to chemical engineering.

Graduate study is no exception to the heuristic that the quality of the supply material dictates the quality of the product. Our recruiting program was organized in an effort to combat the demographics of future shortages of incoming graduate students. For

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***Graduate study is no exception to the heuristic that the quality of the supply material dictates the quality of the product. Our recruiting program was organized . . . to combat the demographics of future shortages of incoming graduate students.***

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example, the national number of PhDs in science and engineering has been forecast by Atkinson<sup>[1]</sup> to have an annual shortfall from 1,000 to 10,000 degrees during the period from 1995 to 2010. Atkinson indicates that this will be the result of a "cumulative shortfall of several hundred thousand scientists and engineers at the baccalaureate level by the turn of the century." While many such studies differ in quantitative predictions, the qualitative trends are almost always similar.

The basis for our recruiting changes was obtained from a study by P.B. Brown<sup>[2]</sup> of 250 graduate programs which ranked the reasons that resulted in a graduate student's choice of a particular school (other considerations being equal). The five criteria highest on the list were:

- *Competitive financial assistance*
- *Personal contact (letters, phone, etc.)*
- *Referrals exchanged with colleagues*
- *Promotional materials on programs*
- *Subsidized visits for promising students*

Most academics could easily list other, less tangible and perhaps more vital, criteria—such as expertise in a research area, size of faculty and program, reputation, location, etc. However, such changes are more far-reaching and less easily addressed by a pilot program than the five criteria listed above.

The principal ingredient of our program was the intellectual and energetic commitment of department personnel. Since the faculty were already occupied with other important projects, our first step was to determine resources in the form of time and funds. These were obtained by a re-

organization of department committee priorities and through the funding of a two-year pilot program by the Graduate Dean.

The departmental involvement in graduate recruiting increased from 10% to 40% of the faculty during this period. Most importantly, an able administrative assistant consistently managed the program details (communications, record keeping, expenses, etc.) as one of her primary functions. For example, letters progressively tailored to an individual's interest are initiated by the administrative assistant to ensure that only a small amount of time separates communications between an inquirer/applicant and the department. Any student who has his/her GRE scores sent directly to the school is automatically sent an application packet.

The Graduate Dean was naturally concerned about graduate recruiting across the institution. He agreed to fund our two-year pilot program with two provisos: (1) that we obtain a mid-point program evaluation by a consultant, and (2) that we make the results of the pilot program available to the entire campus.

### HIGHLIGHTS OF THE PROGRAM

In addition to our efforts to address Brown's five criteria for cost-effective recruiting, some innovative aspects of our program are:

- We made a professional-quality video tape, complete with music and voice-overs, that describes faculty research, the department, the school, and the living environment. As a rule-of-thumb, the cost of such a tape is \$1000/minute for a nominal fifteen-minute tape. At the suggestion of our consultant, we shipped a copy of this tape to every U.S. inquirer.
- Each year we took part in the Student Career Fair held at the annual AIChE conference, via a visually attractive display booth staffed by a faculty member. About five hundred students attend this event each year.
- We held an annual Department Open House, principally for people from local industry who hold undergraduate degrees in chemical engineering or chemistry. The event included brief presentations, a poster session highlighting departmental research, and laboratory tours. About 1500 letters of invitation were sent to members of AIChE and ACS in the Denver area, resulting in twenty attendees and about forty requests for more written information.
- We identified sister institutions which might be sources of incoming students and began an exchange program of seminar speakers with them. At each seminar away from campus, faculty invited interested students for a meal to discuss graduate school.
- We revised the review process so that each of three faculty members independently evaluated the completed applications, both for ad-

mission and for financial support. Soon after each application was evaluated, the review committee met to finalize admission/aid decisions and to resolve discrepancies between recommendations.

- We began to be more consistent in obtaining international students. Two examples: we began record-keeping on applicant performance from schools abroad, and we began to organize recruiting visits to fine chemical engineering schools in Eastern Europe and the Middle East.

### THE PERSONAL TOUCH: CAMPUS VISIT AND FOLLOW-UP

Of all the components of our enhanced recruiting program, one of the most important to its success was the visit of prospective graduate students to our campus. The close faculty interaction with prospective students and our location both make us think the campus visit deserves a ranking close to the top of Brown's list of cost-effective recruiting measures.

Prior to designing our procedures, we spoke with several of our own students regarding their experiences in interviewing at other universities as prospective graduate students. Several of the key points that emerged from these conversations which later guided the construction of our campus visits were:

- It is vital to have close personal interaction with at least one host faculty member who, ideally, should have the same responsibilities that were fulfilled by Dr. Chehead in the opening case study.
- Efforts should be made to have the student interview the faculty regarding his or her own research interests and programs; visits dominated by interviews with other graduate students and post-docs were not perceived as useful.
- Individual student visits are more useful than one group visit. Individual students relate to individual faculty, but students visiting in a group have more in common with each other than with the host institution.
- Quick departmental follow-up after the visit was a key in solidifying the student's interest and commitment.

**TABLE 1**  
**CEPR Graduate Recruiting Results**

Year	1992	1991	1990	1989
Total Applicants	103	51	30	26
a. National Origin				
Foreign Applicants	90	41	?	?
U.S. Applicants	13	10	?	?
b. Graduate Record Exam				
Verbal Score	511	497	510	427
Analytical Score	622	576	587	527
Quantitative Score	753	739	725	698
c. TOEFL Score (Foreign Appl.)	601	592	575	581
Total Applications Accepted	50	38	27	19
Total Accepting Offer	15	17	15	8
Total Registering in Fall	not avail.	14	12	7

Immediately following the student's visit, a recommendation concerning an offer was solicited from each faculty. Within one week, each qualified visitor received a personal letter from the Chair of the Graduate Affairs Committee (GAC) notifying the student that an offer would be forthcoming and recounting highlights of our research and educational programs. This letter was also used to remind the prospective student of acceptance deadlines. Official graduate school notification of the offer followed within one to two weeks.

Closing on prospective students was accomplished by two different mechanisms. Some candidates simply accepted the offer by returning the required materials. For others, further follow-up involved personal calls from the GAC Chair inquiring about the student's status and time-frame for a final decision. Again, the personal touch was perceived to be a key to successfully closing with our more highly recruited candidates.

## **PROGRAM EVALUATION**

The evaluation of the success of the two-year pilot recruiting program is quantified in Table 1. From the data in the table we conclude that our applicant pool has increased substantially both in quantity and quality over the course of the program. After the initial year of the program we invited a graduate recruiting consultant, Donald G. Dickason, to critique the program and to provide a campus-wide seminar on graduate recruiting.

## **FUTURE PLANS: FEEDING THE PYRAMID**

As outlined above, our effort at turning inquiries into applications, and applications into new students has been fairly successful. One area for future improvement is what we call "feeding the bottom of the pyramid," based on a metaphor by Don Dickason. The pyramid consists of the layers involved in the graduate school process, starting with inquiries and ending with degrees granted, each layer being smaller than the one below it.

We plan two additional recruiting efforts in the future. The first is to begin a summer internship program for juniors who are considering graduate school. This will provide exposure to challenging research problems and lead to more graduate applications, both to other institutions and to CSM. The summer research program will also be used to strengthen our women and minorities recruiting programs. NSF has an active program which funds such undergraduate research.

The second plan is to develop a hypertext recruiting document for distribution to prospective students. Hypertext is a method of communicating information in which the reader can move freely through a document, pausing only at interesting points by "clicking" on "buttons." (Modern Windows or Macintosh help systems are an example of hypertext.)

The hypertext document, which will complement our recruiting video, has a number of advantages. The first is that it can be modified quickly and at little cost; in contrast, our video has a shelf life of two years, with significant modification costs.

The second advantage of our hypertext document is that the reader can be highly selective from among a vast amount of information. For example, a reader could easily locate the syllabus of an interesting course, consider a research area in detail, or skip over these in favor of learning about living or recreational conditions in the Golden area. Such a wealth of information might be a boring read in a conventional document, but we believe that hypertext will render it manageable for both the reader and the producer. Our plan is to develop the document using existing hypertext shell/hardware for the Macintosh before porting it to a Windows hypertext system such as Toolbook.

The programs listed above have the potential, not just of increasing CSM's share of a fixed pool of applicants, but of increasing the size of the pool. Our observation, which we are sure is not unique, is that many talented students never consider graduate school simply because they have had little or no exposure to what faculty and graduate students do when they disappear behind their laboratory doors. Increased marketing efforts will, at a minimum, help students make more-informed decisions.

## **ACKNOWLEDGMENT**

We gratefully acknowledge the financial support of Dean Arthur J. Kidnay and former Dean John A. Cordes for this pilot program. Donald G. Dickason was, at the time of his consultancy, Vice President for Higher Education, Peterson's Guides; he is currently Vice Provost for Enrollment Management, Drexel University.

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# AN INTRODUCTION TO THE FUNDAMENTALS OF BIO(MOLECULAR) ENGINEERING

BRUCE R. LOCKE

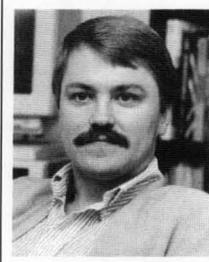
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This is a course intended for first-year graduate students or seniors in chemical engineering and the physical and chemical sciences who may have a minimal background in the biological sciences and who have strong quantitative skills, including knowledge of linear algebra, calculus, and ordinary and partial differential equations. The course emphasis is on combining fundamental principles from physical chemistry, including thermodynamics and (non-linear) chemical kinetics (including irreversible thermodynamics), transport phenomena, and colloidal, interfacial, and molecular science to understanding a wide range of phenomena in biological and biochemical systems that are important in the current applications of biotechnology and in our understanding of living systems for future applications of biotechnology.

The goals of the present approach are

- to provide an overview of a wide open and rapidly developing field that encompasses material from subjects in the biological sciences, the physical and chemical sciences, and engineering
- to give the student the necessary fundamental information and skills to understand current developments
- to motivate the student to investigate areas that need further development, particularly in the area of molecular level design.

The design of structural and functional features of materials on the molecular scale is essential for modern developments in biotechnology and materials science. Examples include the development of new catalysts and sensors. The general philosophy of the course used to reach these goals involves the consideration of a hierarchy of structure from the molecu-



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lar to the supracellular in light of known organizational features to illuminate gaps in our knowledge and to illustrate how our current understanding may lead to the design of functional units from the molecular to the supracellular levels.

Fundamental aspects are stressed in order to provide a framework for further study of bioengineering in such areas as biochemical engineering, biomedical engineering, molecular (protein) engineering, metabolic engineering, and cellular engineering. This course differs considerably from conventional biochemical engineering courses offered in chemical engineering in that molecular-level concepts are incorporated within a framework of fundamental concepts of (non-linear) chemical kinetics, transport phenomena (viscoelastic fluids), and interfacial and colloidal science. In the modern chemical engineering curriculum it has become necessary for students to understand the relationships between the functional and structural properties of macromolecules; this includes not only conventional treatments of single macromolecules in solution but also dynamic systems of macromolecules functioning together in supramolecular and hierarchal structures.

The merging of chemistry and biology through rapid advances in our understanding of molecular scale events opens up the possibility for rational design of materials on the molecular level. The drive for high specificity, high selectivity, high purity, and increased quality control in the production and processing of many materials has stimulated chemists and engineers to look closely at living systems as models for building materials that have never occurred in nature. The diversity of life on earth provides a framework upon which new developments are being made. For example, our ability to develop new enzymes through site-directed mutagenesis and our understanding of molecular structure and function is giving rise to the creation of completely new artificial catalysts that promote reactions not found in natural systems.<sup>[1]</sup>

A recent work by Peacocke<sup>[2]</sup> reviews the literature on biochemical and biological organization that has

arisen through the initial work of Hinshelwood in the 1940s and 1950s,<sup>[3]</sup> the work of A. Turing in the 1950s,<sup>[4]</sup> and the Brussels school of Prigogine in the 1960s to the present.<sup>[5]</sup> Peacocke overlooks the pioneering work of Rashevsky.<sup>[6,7]</sup> The emphasis of these researchers is on the use of chemical reaction kinetics and transport phenomena to describe spatial and temporal pattern formation in biochemical pathways and cellular structures. It is very revealing to the chemical engineering student that major contributions to this area have been made by chemical engineers through the analysis of chemical reactions<sup>[8-11]</sup> and that the students' own fundamental knowledge of chemical reaction kinetics and transport phenomena can be used to describe, for example, slime mold aggregation,<sup>[12,13]</sup> cell cycle oscillations,<sup>[14]</sup> the formation of zebra and leopard spots,<sup>[12]</sup> the spread of a contagious disease,<sup>[12]</sup> the functioning of the immune system<sup>[15]</sup> and cardiac arrhythmia.<sup>[16]</sup> Important developments in the analysis of chemical reactions<sup>[10,11]</sup> have also aided the advancement of the compartmental analysis of biological systems.<sup>[17]</sup> Peacocke only reveals part of the story, however, by not clearly illustrating the connection between the kinetic and systems ideas and the vast wealth of knowledge on the molecular structure of biological macromolecules that has been developed in the last twenty to thirty years. In addition, very recent developments in

***Fundamental aspects are stressed in order to provide a framework for further study of bioengineering in such areas as biochemical engineering, biomedical engineering, molecular (protein) engineering, metabolic engineering, and cellular engineering***

mechanochemical theory that links mechanical motion of molecular structures such as muscle and gel fibers to the chemical composition of the molecular structure<sup>[18,19]</sup> and solution are not fully addressed.

The details of molecular structure and function arise through introductions to molecular biology,<sup>[20,21]</sup> macromolecular science,<sup>[22-24]</sup> intermolecular interactions,<sup>[25]</sup> and recent studies on mechanochemical coupling.<sup>[18]</sup> Intermolecular forces are responsible for the specificity and functioning of most biological macromolecules by giving rise to biomolecular recognition. Biomolecular recognition arises through the simultaneous action of a large number of fairly weak hydrogen bonds, and van der Waals, electrostatic, and hydrophobic interactions arrayed in unique geometrical configurations and acting cooperatively. This is a key concept that is stressed throughout the course because it is the basis for substrate binding to, for example, enzymes, cell surfaces, and antibodies.

The overall structure of the course consists of four parts that progress from a description of structure to the analysis of function (see Table 1). The first part of the course begins with an overall view of life and living systems and progresses to descriptions of cellular and molecular level features. The second part of the course seeks to develop the fundamental principles governing the interactions between macromolecules and small molecules, macromolecules and other macromolecules, and macromolecules and surfaces. The third part seeks to explore the dynamic features of many macromolecules interacting in metabolic pathways, and the fourth part seeks to explore the area of multiple interacting cells, or other subunits such as organelles, through introductions to multicellular communication through direct and indirect interactions and population models.

The mechanics of the course relies heavily on student involvement through term projects and class reports. Table 2 (next page) shows some examples of term papers. Each student is also responsible for presenting the general background material necessary for understanding the subject of their term paper. For example, the student discussing delivery of drugs to the brain also presents an introductory lecture on the analysis of facilitated diffusion.

**TABLE 1**  
**Outline and Major Topics**

*Overall Introduction*

*Part I: Introduction to the structure and organization of life and living systems*

- Biodiversity-sources of materials and inspiration
- Structure of cells and subcellular components
- Molecular components of living systems

*Part II: Molecular level interactions—biorecognition*

- Physical/chemical properties of macromolecules
- Intermolecular forces that stabilize macromolecular structure
- Biological recognition-relationship between structure and function
- Macromolecular interactions with surfaces and surface forces that govern these interactions

*Part III: Intracellular phenomena—The dynamics of multiple interacting macromolecules*

- Metabolic pathways-multiple macromolecules working together in sequence or parallel
- Design and development of complex artificial metabolic systems

*Part IV: Extracellular phenomena—The dynamics of multiple interacting cells*

- Multicellular processes—chemical communication between cells
- Towards a hierarchy of direct and indirect interactions

## COURSE OUTLINE AND DISCUSSION OF TOPICS

The introductory material for this course reflects a very broad and open-minded perspective on the field of biotechnology. In a general sense, one may consider biotechnology as the use of *biomaterials* (*i.e.*, molecules, combinations of molecules, cells, and tissues derived from living creatures) for feedstocks, processing tools, products, and as prototype models for new materials. Although we do not use the narrow definition of biotechnology that includes *only* the products of genetic engineering methods, it is clear that recombinant technology is making great inroads in a wide variety of new applications and that an understanding of recombinant methods is crucial. Perhaps the unique feature of this course is the concept that known biomaterials can be considered as models for the development of new materials. Protein engineering is the best known example of this; however, other examples include biomineralization, facilitated transport processes, and metabolic engineering.

From an engineering perspective, our major interest in biotechnology arises from the use of biomaterials as feedstocks, as processing tools, as products, and as an inspiration for creating new materials. Biomaterials encompass a large range of entities, from relatively simple organic compounds such as penicillin and amino acids, to complex macromolecules such as proteins and vitamins, to complete organisms such as yeasts, plants, and animals. Biomass as a feedstock for the production of alcohol and microorganisms as processing tools for food production and waste treatment have long been used. New bioprocessing tools include immobilized enzymes as industrial and consumer catalysts, recombinant bacteria for the production of eucaryotic proteins, and transgenic cows for producing human proteins.

From a long-range view, the most exciting developments use biomaterials to create new materials that have never occurred in nature. A very interesting example is the development of synthetic heme for the extraction of oxygen from water for life support in the ocean.<sup>[26]</sup> Biomimicry for synthesizing new materials is also rapidly advancing.<sup>[27]</sup> The 1988 Nobel Prize in Chemistry was awarded to D.J. Cram for his work on the design of molecular hosts and complexes. This merges synthetic organic chemistry and biochemistry to create new and exciting materials. Cram states that "evolution has produced chemical compounds that are exquisitely organized to accomplish the most complicated and delicate of tasks . . ." and his achievements demonstrate that we can build upon what evolution has produced.

**TABLE 2**  
**Sample Term Paper Projects**

- The Role of Recombinant DNA Technology in the Degradation of Pesticides and Herbicides
- Biological Pattern Formation: Temporal Oscillations in the Eucaryotic Cell Cycle
- Drug Delivery to the Brain: Facilitated Transport
- Enzyme Engineering
- Biodegradation of Oil Spills
- Genetic Engineering for Enhanced Separation Processes

### **PART I**

#### ***Introduction to the Structure and Organization of Life and Living Systems***

The diversity of life that currently exists on earth, and that has ever existed on earth, is a tremendous source of substances and inspiration for the development of new materials. Prior to describing and discussing this diversity it is useful to consider the unique features of living organisms. Students generally recall from high school biology that all creatures grow, reproduce, consume, and excrete materials and energy from and to the environment, and that all living things eventually die. This is a useful beginning for the analysis of life, and the students may even recognize that there are entities such as viruses that are on the boundary of living and non-living that are difficult to clearly classify. Other general features of life that students will easily come up with are the cell theory and the theory of evolution. The detailed discussion of these two theories is of central importance for understanding and analyzing the structure and dynamics of living systems.

Students trained in the physical and chemical sciences should be motivated at this point to ask questions such as: Do living systems obey the basic laws of physics? Certainly material and energy balances apply—but what about the second law? These ideas are succinctly expressed by Schrodinger,<sup>[28]</sup> who speculated that the dynamic aspects of living systems are related to structural aspects through large molecules, and that these structural molecules and relationships are of special significance for living systems.

"...it has been explained that the laws of physics, as we know them are statistical laws. They have a lot to do with the natural tendency of things to go over into disorder. But, to reconcile the high durability of the hereditary substance with its minute size, we had to evade the tendency to disorder by 'inventing the molecule,' in fact, an unusually large molecule which has to be a masterpiece of highly differentiated order, safeguarded by the conjuring rod of quantum theory. The laws of chance are not invalidated by this 'invention,' but their outcome is modified. The physicist is familiar with the fact that the classical laws of physics are modified by quantum theory, especially at low temperature. There are many instances of this. Life seems to be one of them, a particularly striking one. Life seems to

be orderly and lawful behavior of matter, not based exclusively on its tendency to go over from order to disorder, but based partly on existing order that is kept up ...

Further aspects of ideas from irreversible thermodynamics<sup>[5]</sup> will arise later in the course. However, the main idea in the beginning is to stress that there are important connections, as Schrodinger stated, between the need for macromolecules of "highly differentiated order" and dynamics of living systems, *i.e.*, the organisms' struggle against the forces of entropy. Although he referred primarily to macromolecules that carry genetic information (DNA's role and structure were unknown at the time) and the need for the long-term stability of such macromolecules, it is clear that the general ideas include other macromolecules that make up living organisms. (More recent criticisms of several other aspects of Schrodinger's ideas can be found in Kilmister.<sup>[29]</sup>)

Macromolecules make up the 'first' level of structural 'order' in living systems. They are held together first of all by covalent bonds and secondly their active structure arises through a number of intermolecular forces and solution mediated interactions. Introduction to the basic classes of macromolecules, *i.e.*, nucleic acids, proteins and carbohydrates, can stress the relationship between structure and function. The assembly of lipids into membrane structures is a good example where the molecular structure of individual lipids gives rise to the structure and function of the membranes that they form. Membrane structure and the organization of lipids into micelles, liposomes, and other structures is an important area to consider in detail since it is the basis of all 'higher level' compartments (organelles) in living systems, and it has major applications in separation and reaction processes.<sup>[30]</sup>

Mere descriptions of the hierarchal structure of taxonomy,<sup>[31]</sup> cells, subcellular organelles,<sup>[32]</sup> and molecular components of living systems can be somewhat dry without constant reference to questions such as: Why are plants, animals, and cells of particular sizes? What type of interactions (*i.e.*, direct or indirect) govern the relationships between different hierarchical levels? (For this latter point, see Part IV.) The engineering student, trained in transport and kinetics and scale-up principles, should be able to postulate and test ideas to explain these and other physical biology features.<sup>[33-35]</sup> Concepts from mass transfer and fluid dynamics can be used to describe the structure of various sea creatures.<sup>[36]</sup> In addition, it benefits the student greatly if key features of various levels of description are illustrated. For example, in discussing the taxonomic levels of living organisms it is useful to describe which organ-

isms are used directly by man and for what purpose they are used and why they are used. When discussing the structure of eucaryotic organisms, aspects of intracellular processing such as in the secretion and post translational processing of insulin<sup>[37]</sup> or the transport of materials in and out of the cell<sup>[38]</sup> can be considered in light of their effects on producing eucaryotic proteins in procaryotic cells and in analogy to the processing required in chemical plants (*i.e.*, well-defined regions for reactions and extensive material sorting and purification structures<sup>[39]</sup>).

## PART II

### Molecular Level Interactions—Biorecognition

Once the student has a clear idea of the multiple levels of hierarchal structure of living systems from the molecular to organelle to cellular to organism discussed above, it is useful to continue with a study of the physical/chemical properties of biological macromolecules. Basic ideas from colloidal science including thermodynamic, hydrodynamic, and electrokinetic properties can be introduced within the context of the student's understanding of transport phenomena and physical chemistry. There are a number of excellent references for this area.<sup>[22-24,40]</sup> General physical/chemical features of macromolecules such as size, surface area, charge, and shape should be considered in light of their effects on separation (chromatography, filtration, solubility) and reaction (immobilized enzymes and cell) processes, and in addition to point to further study of how these macromolecules function in groups or assemblages such as membranes, and sub-cellular organelles.

Intermolecular forces that stabilize macromolecular structure can be presented by first considering the nature and origin of intermolecular forces.<sup>[25]</sup> Many aspects of fundamental importance such as the nature of van der Waals forces, hydrogen bonding, and dipole and hydrophobic interactions can be considered. Many of the fundamental aspects have been well developed and current experiments<sup>[41]</sup> using the atomic force microscope have led to interesting advances in, for example, molecular rearrangements upon receptor ligand binding. One major area that needs further development is a quantitative treatment for the hydrophobic effects.

Biological recognition and the relationships between structure and function are key areas that can be considered in much detail. Qualitative examples such as enzyme catalysis (*e.g.*, a serine protease such as chymotrypsin<sup>[42]</sup>), antibody binding (avidin/biotin affinity chromatography<sup>[43]</sup>), cell surface interactions, and facilitated membrane transport (oxygen binding by hemoglobin and myoglobin<sup>[44]</sup>) can be de-

scribed in detail. The quantitative description of these systems can be considered first from the thermodynamic approach<sup>[45-47]</sup> where binding equilibria are developed and second from the kinetic approach through Michaelis Menten type kinetics. Smoluchowski theory and Brownian motion<sup>[48]</sup> can be used to discuss diffusional limitations. In addition, recent work on the induced fit<sup>[49]</sup> and directed binding is useful in developing the dynamic approach to macromolecular recognition.

Macromolecular interactions with surfaces and surface forces that govern these interactions are vital for understanding many biochemical separation and reaction processes such as affinity chromatography and enzyme immobilization procedures. An understanding of surface interactions is also necessary for biofouling in industry, commerce, and biomedical devices. The molecular basis for adhesion of biological macromolecules on cell surfaces to inorganic matrices can be approached from the fundamental perspective as developed by Israelachvili<sup>[25]</sup> and in light of recent advances in active site directed binding.<sup>[41]</sup>

### **PART III**

#### ***Intracellular Phenomena: The Dynamics of Multiple Interacting Macromolecules***

One of the main goals of this course is to foster development of links between the dynamics of macromolecules working together and the structural features of the macromolecules and their complexes. The chemical engineering perspective for analyzing multiple linear and nonlinear chemical reactions in convective-diffusion processes can be used as a basis for analyzing metabolic pathways (lumping analysis,<sup>[50]</sup> modal analysis,<sup>[51]</sup> metabolic models,<sup>[52]</sup> cybernetic models<sup>[53]</sup> such as glycolysis, the regulation of protein synthesis, and the energetics of active transport in cell membranes<sup>[44]</sup>). This is exemplified in the development of reaction-diffusion work from both chemical engineering and biological literature. The view of the reaction processes, however, must go beyond treating the reactants as species without structure since biological structures are dynamic entities that, for example, change shape on substrate binding and that exhibit a wide range of allosteric and cooperative behaviors.

Biomechanical theories for the chemomechanical aspects of structure formation such as muscle action and cell motion can be considered within the context of advanced transport phenomena as elaborated by Murray, *et al.*<sup>[18]</sup> The swelling of (bio)polymers and the electrokinetic effects of applied electrical fields on (bio)polymers can be treated within the context of the engineering students' background in continuum

mechanics as is appropriate for an introductory class.<sup>[54,55]</sup> This area is also important for the development of devices to convert chemical energy to mechanical work with little heat generation. Both of the above chemical and mechanochemical theories are useful for the design and development of complex artificial metabolic systems and structural units.

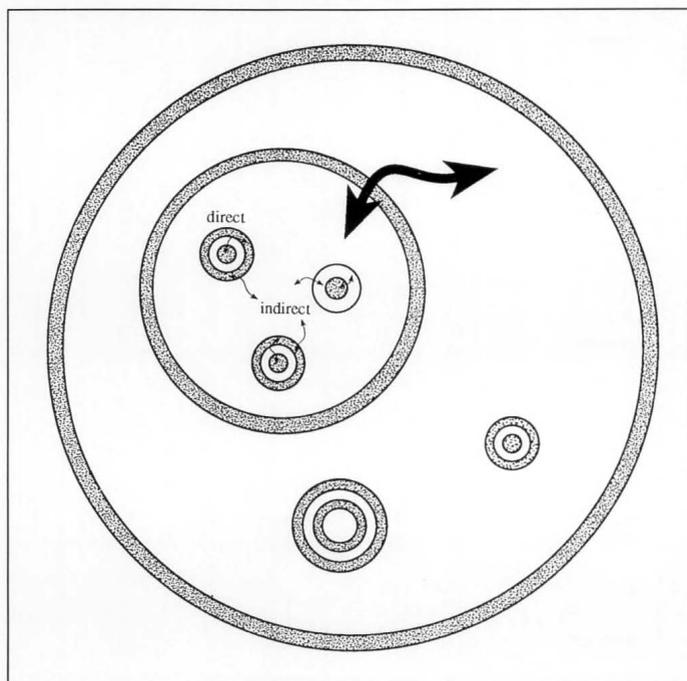
### **PART IV**

#### ***Extracellular Phenomena: The Dynamics of Multiple Interacting Cells and Subunits***

The last level considers direct and indirect interactions for multicellular and multi-subunit (*e.g.*, organelles) processes. Figure 1, a schematic view of such interactions, shows features very similar to the structure of a eucaryotic cell. Direct interactions between cells is important for a full understanding of tissue function and development as well as for such systems as immobilized cells or enzymes in membranes. Indirect interactions are important for bioreactor systems where cells, particles of immobilized cells, and particles of immobilized enzymes communicate through the bulk solution of well-mixed reactors. This area is currently not covered in detail for undergraduates; however, graduate students can appreciate these aspects through comparison to advances in chemical reactor analysis.<sup>[56]</sup> In addition, an introduction to population models<sup>[52,57,58]</sup> is necessary for understanding the growth of microbial organisms in natural and reactor processes.

### **CONCLUSIONS**

There is currently a need for an introductory-level course for the engineering and physical and chemical sciences student that will develop the molecular and hierarchical organizational features of biotechnology, herein considered in a broad sense as the use of biomaterials (*i.e.*, molecules, combinations of molecules, cells, and tissues derived from living creatures) for feedstocks, processing tools, products, and as models for new materials. The course described in this paper seeks to integrate current and past developments from a wide range of fields into the chemical engineering curricula, to instill in the student the necessity for reading and understanding materials from a broad range of subjects and to inspire students to seek answers to unknown questions about the applications of the biosciences for improving our quality of life. This approach can be accomplished by building upon a fundamental understanding of transport phenomena and chemical kinetics through the introduction of analysis of non-linear chemical reaction-convective-diffusion processes, non-Newtonian and viscoelastic mechanics, colloid and interfacial



**Figure 1.** Hierarchy of direct and indirect interactions science, and population balance approaches. This approach will lead to additional coursework to introduce molecular transport theories,<sup>[59]</sup> statistical mechanics, and even quantum mechanics for further study of bio(molecular) design.

## ACKNOWLEDGMENT

I would like to thank Dr. Pedro Arce for his invaluable comments on the text of this manuscript and for many useful conversations on the general subject of direct and indirect interactions in systems with hierarchical levels of structure.

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Continued on page 203.

# A COLLOQUIUM SERIES IN CHEMICAL ENGINEERING

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In describing a course on technical talks, Felder<sup>[1]</sup> points out the importance of communication skills for all practicing engineers. The significance of effective communication skills is also underlined by Hanzevack and McKean<sup>[2]</sup> in a discussion of effective oral presentations as part of the senior design course for chemical engineers. In both references, the reader can find suggestions for successful oral presentations. Furthermore, in the latter paper a "presentation feedback form" is illustrated which can be used not only for evaluation of an oral technical presentation but also for drawing the attention of the speaker to some important points during the organization of the presentation.

Most undergraduate programs in chemical engineering include a course on how to improve oral communication skills, and some graduate programs further develop those skills through technical presentations as part of a course. Good written and oral communication skills are the goals of the Depart-

**Costas Tsouris** recently received his PhD in chemical engineering at Syracuse University. He worked with Professor L. L. Tavlarides in the area of liquid dispersions.



**Sotira Yiacoumi** is finishing her PhD in civil engineering at Syracuse University. She works with Professor Chi Tien in the area of uptake of metal ions and organic compounds by natural systems.



**Cynthia S. Hirtzel** is Professor and Chairperson of the Department of Chemical Engineering and Materials Science at Syracuse University. Her research interests are in the areas of colloidal and interfacial phenomena, adsorption/desorption phenomena, and stochastic analysis of modeling of engineering systems. She is also actively involved in technical outreach to pre-college students. (Photo not available)

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*The presentations are designed to simulate a thesis or dissertation oral examination. The duration of each seminar (which the speakers are encouraged not to exceed) is about thirty minutes.*

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ment of Chemical Engineering and Materials Science at Syracuse University. Faculty and students are both concerned with the student's ability to communicate technical expertise.

A seminar program called "Colloquium Series in Chemical Engineering and Materials Science" (ColCEMS) has been initiated and is run by the students in collaboration with the faculty to satisfy this mutual concern. The ColCEMS operates during the fall and spring semesters of the academic year, as well as during the summer sessions. It is a step beyond the summer seminar program which was initiated at Virginia Polytechnic Institute and State University.<sup>[3]</sup> The purpose of this article is to describe all the activities within the colloquium series and to provide an example for students in other schools to follow.

## OBJECTIVES

The main objectives of ColCEMS are

- to improve the communication skills of graduate students
- to share knowledge obtained from recent research activities
- to exchange ideas and develop constructive criticism.

Although the above objectives are all equally important, good communication skills are necessary in order for a speaker to share ideas and results with an audience and to receive feedback in the form of constructive criticism. This is a reality that is recognized by all students, and it serves to strengthen their determination to improve their own communication effectiveness.

The departmental seminar program that runs in parallel is a rich source for examples of both good and bad presentations. Although the main objective of the department program is the exchange of ideas, due to the ColCEMS students are able to see beyond

the speaker's ideas and findings. In this way they develop a rounded critical opinion of both the speaker and the presented work.

## SCHEDULE

Preparation for the subsequent seminar schedule starts even before the current one ends. The coordinators encourage all graduate students to submit a seminar title and a preferred date for its presentation, although participation is voluntary for both speakers and audience members. Not many students come forward, however, until they have a considerable amount of information to share, usually in the second or later year of their graduate studies.

To complete the schedule (which consists of approximately twelve seminars) the coordinators invite research associates, faculty members, and even some students and faculty from other departments who have similar backgrounds and interests. In this way the seminar program covers many research areas and attracts people with diverse backgrounds.

The participation of research associates and faculty, both as speakers and as audience, is very important for the ColCEMS since it engenders more

departmental attention and encourages the speakers to carefully prepare their presentations. A good balance between graduate students, research associates, and faculty (corresponding to the number of people in each category within the department) is maintained.

The seminar schedule is announced two weeks before the first presentation. Each speaker and each member of the department receives a copy of the schedule, and additional copies are distributed to faculty members in other departments at Syracuse and at SUNY/Environmental Science and Forestry where chemical engineering faculty members collaborate on joint research projects. Finally, a copy of the schedule is sent to the *Syracuse Record*, a weekly campus newspaper.

The seminar topics for 1991 are shown in Table 1. The table also serves to demonstrate the diversity of research interests in the department. Seminars of general interest, such as "All You Wanted to Know About Physics and Were Afraid to Ask," "Quantum Gravity," and "The Human/Animal Bond: Interaction Among Pets and People" are exciting and well received by the audience. Our goal is to have such

**TABLE 1**  
**Topics: 1991 Colloquium Series in Chemical Engineering and Materials Science**

### Spring 1991

- Modeling of the Electrostatic Corona Discharge Reactor
- Approximate Solutions to Intraparticle Diffusion Equations
- Transport of Ions Near Fractal Electrodes
- Solvent Extraction Separation of Main Group Elements with Macrocyclic Polyethers
- Adsorption of Metal Ions from Aqueous Solutions
- Design of Polymer Membranes for Superior Separation Properties
- Precipitation from Homogeneous Solution: A New Technique for the Preparation of Catalysts and Catalyst Supports
- Application of Impregnated Ceramic Membranes for Metal Ion Separation from Hazardous Waste Streams
- Monte Carlo Experiments for Desorption of Molecules from Solid Surfaces
- Computer Modeling of Electromigration
- Design of a Laboratory Supercritical Extraction and Oxidation System for PCBs
- Membrane Processes for Gas Separations
- A Membrane Process for In Situ Removal of Carbon Dioxide from Diving Atmospheres

### Summer 1991

- Droplet Breakup in Liquid Dispersions
- All You Wanted to Know About Physics and Were Afraid to Ask
- Relationships Between the Chemical Structure of Fluorine-Containing Polyimide Membranes and Their Gas Permeability
- Quantum Gravity
- An Experimental Demonstration of Facilitated and Active Transport in the Human Placenta
- Properties of Amphoteric Oxides: Surface Charge Development in

### Aqueous Solution and pH Dependence of Metal Ion Adsorption

- Deposition of Diffusive Aerosols
- Evaluation of Adsorption Energy Distribution for Heterogeneous Surfaces
- Simulation of Bubble Dynamics
- Electrical Breakdown of Polymers
- Acoustics of Bubbly Liquids
- The Human/Animal Bond: Interaction Among Pets and People

### Fall 1991

- Analysis of Cake Formation and Growth: Formulation and Possible Solutions
- Control of Extraction Columns
- I. Effect of Intrasegmental Mobility on Gas Permeability of Polyimide Membranes
- II. Representation of Gas Solubility and Diffusivity in Glassy Polymers
- Estimation of Parameters in Differential Models by Infeasible Path Optimization
- Interrelationship Between the Source Material for Activated Carbons: Its Structure and Chemical Effects During Hydrogen Adsorption
- Water in Polyimides: Solubility and Transport
- Aerosol Deposition in Fibrous Systems
- Sulfate Adsorption on Mineral Soils
- Magnetism in Thin Films
- Computer Simulation for Adsorption of Molecules on Solid Surfaces
- Development of Inorganic Chemically Active Beads for Metal Ion Separation from Hazardous Waste Streams

seminars not only in the summer but also during the two academic semesters.

## FORMAT

The ColCEMS presentations are designed to simulate a thesis or dissertation oral examination. The duration of each seminar (which the speakers are encouraged *not* to exceed) is about thirty minutes. Overhead and slide projectors are usually used as visual aids, and some speakers include video-tape shows and laboratory equipment to make their talk more understandable. Due to the diversity of backgrounds in the audience, the seminars usually start with a relatively long introduction. Only clarification questions are allowed during the seminar, but the presentation is followed by a question-and-answer session directed by the seminar coordinators. The duration of this session is not fixed—it depends on the number of questions and may last anywhere from five to twenty minutes.

There are two seminar coordinators elected at the end of the summer colloquium series. They are responsible for preparing the seminar schedule at the beginning of each semester, arranging for financial support, arranging for refreshments, announcing each weekly seminar, arranging for the room and

any visual aids needed, introducing the speakers, announcing the following week's speaker, and directing the question-and-answer session at the end of each seminar.

## ANNOUNCEMENT

Each seminar is announced in the weekly campus newspaper *Syracuse Record*, and an announcement is also made in the department by the coordinators. The coordinators ask the speaker for an abstract of no more than three hundred words, which is then typed on a special form with the seminar title, speaker's name, and date, time, and place (see Table 2). Copies of this announcement are placed in the mailboxes of students, research associates, faculty, and staff, usually one day before the seminar. Announcement copies are also placed on bulletin boards where everyone can see them.

## SEMINAR DAY

The seminars are usually scheduled for Fridays, although in the summer of 1991 they were on Thursdays. The meeting time of 12 noon is set to avoid class conflicts. Between 12:00 and 12:15, attendees can socialize, and at 12:15 the seminar begins with the introduction of the speaker by one of the coordinators. A question-and-answer session, directed by the coordinator, is held after the seminar, usually between 12:45 and 1:00.

Refreshments, usually juice and fruit, are purchased with Graduate Student Organization or departmental funds just before the seminar. One of the two coordinators is responsible for procuring the refreshments, while the other readies the room and arranges for any visual aids the speaker may require.

Just before the seminar, a sign-up sheet is passed around the audience, solely for statistical purposes. These sign-up sheets, along with the abstracts and seminar schedules, are kept in the ColCEMS files.

From the data obtained during the first year, we have been able to determine that the audience primarily consists of chemical engineering graduate students, research associates, and faculty—with occasional participation of graduate students and faculty from other engineering and science departments. A number of faculty members attend all seminars, and the remainder attend according to their research interests.

## AWARDS

At the end of the last seminar of each semester, the audience is asked to vote for their choice of the

**TABLE 2**  
**Typical Announcement**

**COLLOQUIUM SERIES**  
in  
**CHEMICAL ENGINEERING AND MATERIALS SCIENCE**

**SPEAKER:** Ai Chen  
Graduate Student  
Chemical Engineering and Materials Science

**TOPIC:** Computer Simulation for  
Adsorption of Molecules on Solid Surfaces

**DATE:** Friday, November 22, 1991

**TIME:** 12:15 PM

**PLACE:** 017 Hinds Hall

Adsorption of molecules on zeolite 5A has been studied using Monte Carlo simulations. Site-site potential energies were used to model the adsorbate-zeolite and adsorbate-adsorbate interactions. In the potential energy model, the dispersion, repulsion and electrostatic induction energies have been taken into account for monatomic molecules. In addition to the above terms, the quadrupole-quadrupole and ion-quadrupole interactions have been taken into account for diatomic molecules. A new Monte Carlo simulation model is proposed based on stochastic Markov process theory to carry out the simulations. A prominent advantage of the model is that it is suitable for massively parallel implementation. The preliminary results for the pure-component isotherms are in good agreement with experimental data. The study for multicomponent systems is still undergoing.

two best seminars. The awards are usually books provided by the department and presented to the winners at the first seminar of the following semester. Also, pointers (useful for seminars) are given to all speakers.

The gifts express the appreciation of all department members for the effort the speakers put into their presentations. They also serve as a motivation for the graduate students to come forward and give a seminar.

## SUMMARY

The graduate students in the Department of Chemical Engineering and Materials Science at Syracuse University, in collaboration with the faculty, have developed a seminar program called the "Colloquium Series in Chemical Engineering and Materials Science," with the objectives of improving the communication skills of graduate students, sharing knowledge, and exchanging ideas. Our experience has been that those objectives have been met. Furthermore, the ColCEMS program has also served as a catalyst for bringing all members of the department closer together. Intellectual relations among graduate students, research associates, and faculty have been enhanced, and everyone has had the opportunity to see beyond the technical skills of the speakers.

We feel that in an academic setting, where people are constantly coming and going over a relatively short period of time, this kind of activity is important for both educators and students. We wanted to share this experience with the readers and to urge graduate students at other schools to initiate a similar program.

## ACKNOWLEDGEMENTS

The authors acknowledge and thank the Graduate Student Organization and the Department of Chemical Engineering and Materials Science for financial support of this seminar program. The help of the seminar coordinators for the academic year 1991-92, Kaaeid Lokhandwala and Michael Norato, is also appreciated. In addition, we wish to thank Ms. Nicole Jones for her expert assistance in preparing this manuscript.

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## A Course on . . .

# ENVIRONMENTAL REMEDIATION

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A new course has been developed at the University of Houston for graduate students and seniors in chemical engineering on the topic of environmental remediation. There are numerous areas throughout the country where soils, surface water, and/or groundwater are contaminated to such a degree that they are unsafe for us to use for business, to reside near, or to consume the water. This has created an increasingly stringent regulatory climate for industry with respect to waste disposal. These conditions were the motivation for development of this course. Today's students must be made aware of waste treatment and environmental reclamation issues in order to function effectively as design, process, and research engineers and managers. A number of our faculty have also begun working on research projects on contaminant transport in soils, dechlorination processes, and bioremediation, evincing the widespread interest in environmental issues within the department.

The purpose of the course is to introduce the students to both the traditional and the developmental methods for removal or destruction of hazardous wastes at contaminated sites and from industrial waste streams. The emphasis of the course is not on hazardous waste management and regulatory issues, but rather on the destruction, removal, and containment methods themselves.

The timeliness of the course was demonstrated by the student enrollment this past spring, the first time the course was offered; with no advertisement, we attracted forty-two graduate students and half of

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***The course concentrates on several aspects of the hazardous waste problem while touching on others only superficially. We are mainly concerned with hazardous wastes in soils, groundwater, and waste-water ponds and tanks.***

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the graduating seniors for the course. The graduates included Master's and doctoral candidates in chemical (twenty-seven), petroleum (one), civil (two), and environmental (ten) engineering, as well as geology (two). Many of the Master's degree candidates were employed full-time in local industry and hence made many interesting and useful contributions regarding problems with waste generation, treatment, and disposal in their companies. The course fulfills a technical elective requirement for undergraduates who have selected the environmental specialty, one of several fields of specialization they can choose.

### COURSE CONTENT

An outline of the course is shown in Table 1. The course concentrates on several aspects of the hazardous waste problem while touching on others only superficially. We are mainly concerned with hazardous wastes in soils, groundwater, and waste-water ponds and tanks. Air pollution is not covered (a separate course on air pollution control is offered in our department).

A typical scenario considered during the course is, for instance, a hydrocarbon spill in subsurface soil, such as from a leaking underground storage tank. The hydrocarbon may be lighter or heavier than water, and hence it may float on or sink below the water table. It may be carried with or dissolve in the groundwater, adsorb to the soil, break down by thermal, chemical or biological means, or volatilize. Obviously, many physical, chemical, and biological processes influence the fate of the spill and our ability to clean it up. Our discussion of various remediation methods includes consideration of these issues.

We concentrate on hydrocarbon wastes, though some discussion of heavy metals and radioactive waste is included. Hydrocarbons are of particular

interest because of the concentration of the petroleum industry in Texas, and because they are common contaminants throughout the rest of the country as well. Of the various methods of contaminant recovery or destruction, we cover bioremediation in the most depth. Though many bioremediation techniques (other than the long-practiced landfarming) are still generally considered developmental, the potential for contaminant destruction rather than removal, the *in situ* treatment options, and the favor bioremediation is gaining with regulatory agencies motivated this selection.

We begin the semester with a brief overview of the origins and the biological and ecological effects of various types of hazardous wastes, including hydrocarbons (oil industry, agricultural chemicals, wood-treatment chemicals, etc.), heavy metals, and radionuclides. These lectures are designed to help the students understand why certain wastes are considered hazardous and why we must be concerned about their uncontrolled release.

We next cover analytical methods that are commonly used to detect and quantify concentrations of contaminants. The methods include gas chromatography (GC) and high performance liquid chromatography (HPLC), and various types of de-

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***The purpose of the course is to introduce the students to both the traditional and the developmental methods for removal or destruction of hazardous wastes at contaminated sites and from industrial waste streams.***

---

tectors used with them; mass spectrometry and its use with GC and HPLC; and atomic absorption spectrometry. There are numerous reference materials on these techniques.<sup>[1-4]</sup>

We also illustrate the methods by which one can measure the concentration of organic matter in waters, such as Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Organic Carbon (TOC), and Total Oxygen Demand (TOD). Chapter 2 of a book on water quality by Tchobanoglous and Schroeder<sup>[6]</sup> is used, though nearly all such books will include a section on these measurements. We also introduce the existence of the standard numbered analytical methods that the Environmental Protection Agency (EPA) requires for detection of various substances in different media (*e.g.*, drinking water or plant effluent water to be released to a river). A recent paper<sup>[6]</sup> discusses the need to consolidate and revise these prescribed methods.

Following these introductory lectures, we take a quantitative look at contaminant transport in porous media, such as in a diesel fuel spill in soil. Professor Kishore Mohanty, an expert in transport processes in porous media, was a guest lecturer for this part of the course last spring. He covered mathematical models that can be used to calculate the rate of movement of a fluid, illustrating its dependence on such parameters as groundwater velocity, soil porosity, tortuosity of pore structure, molecular diffusivity, and capillary pressure. He also explained the mechanisms of drainage and imbibition of groundwater and how these processes affect the movement of nonaqueous phase liquids. A recent review<sup>[7]</sup> is used as a reference, and several other books serve as additional resources for the interested student.<sup>[8,9]</sup> Since this course concentrates on methods that chemical engineers might utilize to remediate a site, these topics are covered only briefly. However, because one must locate a contaminant before devising an optimal cleanup strategy, this part of the course will likely be expanded in the future.

At this point we begin to examine the various techniques that we can apply to reclaim a contaminated site. We begin with the bioremediation methods, spending four to five weeks on the topic.

**TABLE 1**  
**Course Outline**

**Introduction**

- Hazardous wastes—types and origins
- Biological and ecological effects of hazardous wastes
- Introduction to environmental remediation methods
- Analytical methods

**Contaminant Transport Mechanisms**

- Physicochemical and geologic factors
- Mathematical analysis

**Bioremediation**

- Microbiology and growth kinetics
- Methods—*in situ*, surface, bioreactors
- Remedy screening
- Case studies

**Chemical, Thermal and Physical Remediation Methods**

- *In situ* volatilization
- Low temperature thermal
- High temperature thermal
- Supercritical oxidation
- Extraction
- Adsorption
- Case studies

**Regulations**

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***The coursework included two take-home exams in which the students had a week to answer two to three problems. Both conceptual and quantitative problems were used.***

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Because most engineering students have little or no microbiological background, the first couple of lectures cover the basics on bacterial growth kinetics, substrate and oxygen utilization, co-metabolism, and the variety of substances that microbes are known to metabolize. These lectures were given by Professor Richard Willson, who conducts biochemical separations research. He stressed that there is a maximum rate at which microbes can metabolize a substrate and that the rate of metabolism will slow down as substrate concentration decreases. In addition, the concentration of contaminants that can be achieved with biodegradation may not be as low as we require, and many contaminants are not biodegradable or degrade very slowly. The latter includes many chlorinated compounds that, unfortunately, are usually highly toxic and difficult to remove or degrade by other methods as well. Anaerobic microbes appear to dechlorinate hydrocarbons better than aerobic microbes, but the rate is very slow.

Standard microbiology textbooks can be used as references, and *Biochemical Engineering Fundamentals*<sup>[10]</sup> includes mathematical descriptions of substrate utilization and growth rates. Numerous overviews of the use of microbes to degrade environmental contaminants exist; we use a publication by the Office of Technology Assessment<sup>[11]</sup> and several other recent reviews.<sup>[12-14]</sup>

Following this introduction, we examine the various methods by which we can utilize biodegradation for waste removal. These include landfarming and its variations (composting, bioleaching), *in situ* bioremediation with and without additional microbes, and several types of bioreactors.<sup>[12-15]</sup>

Landfarming (the practice of periodically adding fertilizer and moisture, and tilling to expose the contaminated soil to oxygen) has been used in the oil and chemical industries for many years to treat relatively small spills on soil.<sup>[15]</sup> The idea to use *in situ* bioremediation has gained favor in recent years because of its noninvasive nature and typically low cost. In this method, one only has to inject aqueous solutions of nutrients (typically nitrogen and phosphorous sources), oxygen, and sometimes exogenous microbes into the area to facilitate the *in situ* degradation of the offending contaminants. Contaminated groundwater may be treated simultaneously by

pumping it to the surface, treating it through phase separation, carbon adsorption, or other methods, and then typically using it as the water source for the nutrient solution.

We stress that although *in situ* bioremediation has the advantages that excavation is not required, contaminated soils and groundwater can be treated, and manpower and maintenance requirements are low, it also has numerous major limitations. *In situ* bioremediation is typically very slow, so cleaning up a site may take years, low cleanup levels may not be possible, confirmation of cleanup may be difficult (so monitoring may have to be continued for several decades), contaminant migration may occur, low permeability areas may be bypassed and not treated, or the soil may get plugged by the increase in biomass.

An alternative to *in situ* bioremediation that bypasses many of these limitations is the use of bioreactors. We examine several types: the stirred tank reactor can be used for treatment of liquids as well as slurries, whereas trickle bed reactors with a growing biofilm on the packing medium are used with liquid waste streams.<sup>[15-18]</sup> Bioreactors are typically the most expensive method of bioremediation, but are also the most controlled. Treatment times for the same amount of waste are typically shorter than either surface treatment or *in situ* methods, less space is required, and air emissions can be controlled. As with other types of bioremediation, low cleanup levels may not be possible. If soils are to be treated, a significant water source is required to form a slurry. An electrical source is also required. The bioreactor is much easier to study quantitatively than either *in situ* or surface bioremediation methods, and we derive some bioreactor models that utilize the substrate utilization and growth kinetics in this part of the course.

At this point, when the students have several choices of remediation methods in mind, procedures for remedy screening and design are introduced. The critical idea is that one must design and carry out appropriate laboratory studies to test whether proposed remediation methods are likely to fulfill one's requirements. These studies must provide enough information to narrow the choices of remedy, provide data for pilot-scale studies if necessary, and eventually allow one to obtain the necessary permits and design a full-scale process. The EPA provides various guideline documents for treatability studies; we used one for aerobic biodegradation remedy screening.<sup>[19]</sup>

Several case studies are used to illustrate the implementation of bioremediation methods, the decision

processes that lead to their utilization, and the possible pitfalls involved. A well-documented site that is on the National Priorities List (Superfund) is an abandoned wood-treatment facility in Montana.<sup>[17,18]</sup> Both soils and an aquifer are contaminated from uncontrolled releases of creosote and pentachlorophenol during its twenty-three years of operation. *In situ* bioremediation, landfarming in contained land treatment units, and bioreactors for the most contaminated groundwater are all being used. Another wood-treatment facility in Minnesota that has contaminated water with pentachlorophenol is being remediated with a fixed-film bioreactor.<sup>[16]</sup> Numerous other reports of bioremediation application can be found in the waste treatment, water quality, and environmental literature.

Professionals in local industry are also invited to speak to the class about their involvement in bioremediation activities. We had two such guests last spring. The first, Joseph Jennings (President of Waste Microbes, Inc.), presented his company's involvement in treating wastewater ponds and tanks. The company has developed a consortium of microbes that they add along with nutrients and sparging air at the bottom of a body of water. His presentation helped us focus on the common and important issues of whether aqueous contaminants may be stripped into the atmosphere rather than degraded, and whether the addition of exogenous microbes is necessary or helpful.

The second speaker, Sara McMillen (a microbiologist at Exxon Production Research), gave a presentation on bioremediation in general which included her work on composting and Exxon's experimentation with bioremediation in Prince William Sound following the Exxon *Valdez* oil spill (also described in reference 11).

Following bioremediation, we move on to other remediation methods. They are grouped in terms of the physical or chemical means of contaminant separation or destruction utilized. We start with *in situ* volatilization or soil venting, the removal of organic compounds from subsurface soils (and possibly groundwater) by mechanically drawing or venting air through the soil matrix.<sup>[15]</sup> We stress the physical parameters that determine the success of this method, which include the volatility of the compounds, their adsorption into the soil, and the ease of drawing or venting air through the soil.

We next cover low temperature thermal treatment because it also utilizes volatilization, though in a controlled, heated chamber.<sup>[15,20]</sup> In this case, excavation of the contaminated soils is required. In both

methods the off-gases are typically burned or adsorbed on activated carbon or water in scrubbers, depending on the concentration and type of contaminant. An advantage of low temperature thermal is that it allows the recovery of the hydrocarbon if desired.

High temperature thermal operations are considered next. We discuss methods, design parameters, and operating conditions of incineration, vitrifica-

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***Some problems on both exams were designed to illustrate the idea . . . that one has many types of remediation methods to choose from and one must weigh the advantages and limitations of each on scientific, social, and economic scales . . .***

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tion, and pyrolysis. A major advantage of high temperature methods is the greater than 99% destruction of organic contaminants that is usually attainable.<sup>[15,20]</sup> Major scientific limitations include the need for substantial air emissions equipment if elevated levels of halogenated organic compounds or volatile metals are present, and the production of residual ash that might need additional treatment or special disposal. A nonscientific limitation is the societal objection to incinerators near residential areas. High temperature methods are typically very expensive because of the high energy usage, and the permitting process can be extremely lengthy and costly.

Supercritical water oxidation is also included. Last spring this was discussed by Professor Vemuri Balakotaiah, who specializes in analysis of various chemical reactors and reaction mechanisms. He demonstrated how oxidation in supercritical water can provide very high destruction efficiencies—in many cases greater than 99.99%, even with very dilute waste streams.<sup>[21,22]</sup> He also compared the operation and destruction efficiencies of supercritical water oxidation processes with several typical incinerator designs to illustrate their similarities and differences.

The last major technology that we study is separations, specifically adsorption and extraction. An unpublished review by D. W. Tedder at the Georgia Institute of Technology, entitled "Separations in Hazardous Waste Management," is used as an overview of the topic. Activated carbon adsorption is discussed in some detail because of its extensive and long-time use for air emissions control and polishing wastewater.<sup>[23,24]</sup> We also discuss several chemical extraction methods that are used to separate contaminated

sludges and soils into their respective phase fractions: organics, water, and particulate solids. These include the supercritical fluid extraction processes based on carbon dioxide or propane and the Basic Extraction Sludge Treatment (B.E.S.T.) process of the Resources Conservation Company (Bellevue, WA) based on the temperature-dependent separation of water and aliphatic amines.<sup>[15]</sup>

*In situ* soil leaching and the potential use of surfactants are also briefly discussed. While separations processes for soil and sludge decontamination may be considered developmental, they have the advantages of obtaining a reusable oil phase, can be used with high moisture content soils and oil concentrations up to forty percent, and are usually less expensive than incineration or commercial landfilling. The potentially limiting problems include not being able to handle soil clay content above about twenty-to-thirty percent and high volatiles content, and difficulty in handling soils that have been contaminated for extended periods of time because of weathering and adsorption. Again, case studies are included where possible.

Following our study of these major areas, we briefly introduce a number of other methods so that the students are aware of the many options that have been used or are in development. We include solidification and stabilization, which involve the addition of materials that combine physically and/or chemically to decrease the mobility of the original waste constituents. Next are *in situ* and *ex situ* isolation and containment, which involve isolating the contaminated soil from the surrounding environment with physical barriers such as clay caps, synthetic liners, slurry cut-off walls, and grout curtains. Finally, we describe the idea of beneficial reuse, such as incorporating soils containing petroleum hydrocarbons in hot asphalt mix, or using contaminated soil as road base material or construction material for structures such as containment berms.

Regulatory issues are not covered in depth because of time constraints, though the major national legislation is introduced early in the course. It includes the Resource Conservation and Recovery Act (RCRA), the Comprehensive Environmental Response Compensation and Liability Act (CERCLA), the Superfund Amendment and Reauthorization Act of 1986 (SARA), the Clean Water Act (CWA), the Toxic Substances Control Act (TSCA), and Underground Storage Tank (UST) regulations. In addition, the process of obtaining a Record of Decision by the EPA for a remediation plan is described.

We also bring in an outside expert to discuss the

regulatory climate in Texas. Last spring Marilyn Long (Senior Geologist at the Texas Water Commission, Texas' partial equivalent of the EPA), gave a lecture on dealing with hazardous wastes in Texas. She described the various regulatory agencies in Texas and their jurisdictions. She discussed the legal ramifications of statutes, rules, and guidelines, and how a company must work with the regulations and regulators. She also discussed her involvement in several bioremediation and low temperature thermal treatment projects.

## COURSEWORK

The coursework included two take-home exams in which the students had a week to answer two to three problems. Both conceptual and quantitative problems were used. For example, one problem on the first exam gave a sketchy description of a "superfund" site, including volumes of contaminated surface water, groundwater, soils, and sludge at the bottom of a pond, types of contaminants (hydrocarbons and some heavy metals), and a history of the site. An "approved" clean-up scenario was described, which consisted of incineration of the contaminated soils and sludges, use of ash as backfill, natural attenuation of the aquifer (to be monitored), and discharge of the water to a nearby river after polishing. The problem then stated that the responsible party is requesting permission to evaluate the use of bioremediation for the site as an alternative to the selected remedy. The student, as the company's expert on bioremediation, was to outline the types of bioremediation that may be appropriate for each of the contaminated media, outline a laboratory remedy screening study to test the feasibility of his suggestions in the first part, and then describe how he would actually implement an overall reclamation plan utilizing bioremediation for the site. Some aspects of the site description were purposely left vague so that the student could make assumptions or specifications about anything that was not explicitly stated. His solution then had to be consistent with the assumptions made.

Some problems on both exams were designed to illustrate the idea, emphasized throughout the course, that one has many types of remediation methods to choose from and one must weigh the advantages and limitations of each on scientific, social, and economic scales in order to devise an optimal solution.

The students also complete a term paper or project of their choosing. The topics are allowed to range from site characterizations, critical reviews of ongoing site cleanups, critiques of particular remediation

methods, and mathematical models of a method (e.g., reaction kinetics in an incinerator) or contaminant transport. A major requirement for the paper is a critical evaluation of the selected topic. Last spring, specific titles included "Dioxin formation in pulp bleach plants," "Naturally occurring radioactive material accumulated as a result of hydrocarbon production—waste minimization technology," "The MOTCO superfund site: an evaluation," and "Distributed control in wastewater treatment systems." Several students selected topics that were relevant to their present jobs so they could learn something that might help them immediately, whereas others chose such popular topics as the use of bioremediation for the Exxon Valdez oil spill in Alaska.

## RESOURCE MATERIALS

Because of the broad nature of the material that is covered, we do not use a specific textbook. Rather, a number of papers from the literature, as well as chapters from several books, are used (a number of which are cited herein). Literature papers are especially useful for case studies.

A particularly useful resource is a manual prepared by Environmental Solutions, Inc., under contract by the Western States Petroleum Association, entitled *Onsite Treatment: Hydrocarbon Contaminated Soil*.<sup>[15]</sup> It is used extensively for summaries of the various soil-treatment methods. While the manual does not deal with design of the processes, it includes excellent qualitative summaries of various methods, their applicability, advantages and limitations, permitting requirements, whether a method is developmental or proven, costs, capacity and manpower estimates, and references for actual usage of the method. It also provides guidelines for selecting the best method for site-specific conditions, which is very useful. Most of the remediation methods the manual discusses were mentioned above and are touched on at least briefly during our course.

## SUMMARY

The environmental remediation field is changing rapidly as new methods are developed to handle the numerous hazardous substances that pollute the soils and groundwater in many areas of the country. Chemical engineers are ideally suited to work in this field because of our expertise in transport phenomena, thermodynamics, reaction kinetics, and unit operations—all of which are required to quantify the movement of contaminants in the subsurface and devise optimal methods of remediation.

This course is designed to introduce both graduates and seniors to the field. We expect the course

will evolve to include more emphasis on hydrogeology and contaminant transport calculations and increased use of models and design equations to evaluate the applicability and efficiency of methods in different contexts.

Inviting outside speakers from local industry will continue. The speakers were well received and the students welcomed the chance to hear from people experienced with specific remediation technologies.

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# SOME THOUGHTS ON GRADUATE EDUCATION

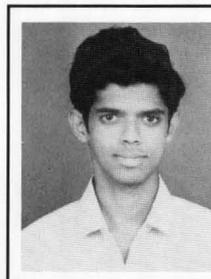
## *A Graduate Student's Perspective*

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Chemical engineering may well be the most diverse of the engineering disciplines, and it is getting broader every year, with practitioners working in such far-removed areas as molecular genetics, microelectronics, and artificial intelligence. In fact diversity and adaptability may be the main advantages we have over other engineers. In the future, chemical engineers will have to be creative thinkers, using their knowledge to expand the frontiers of science, and we must give considerable thought right now to how we can prepare students to face that challenge. In response to this future need, quite a few changes have already been incorporated in the curriculum, but additional improvements will also be necessary if we are to keep pace with future developments and demands.

A natural consequence of progress is the increase in the standard at each level of education. For example, while I was not introduced to computers until the twelfth grade, today's eighth-grade students are already using computers. At the college level, it seems to me that converting chemical engineering into a multidisciplinary field has been reasonably well accomplished in the undergraduate curriculum, and that the curriculum has become more flexible. In order to prepare students for the next step (either graduate school or industry) a number of changes have occurred—undergraduate research being the most significant, in my opinion, since it gives the student a flavor of graduate school and research.

The logical sequence now is for graduate education to follow suit and to introduce students to some of the characteristics of faculty/industrial research careers. I do not claim that this has not already been done, but I do wish to explore opportunities for further improvements. I realize that there are professors who are better qualified and more experienced to address this issue than I am, but I would like to



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offer my ideas—from a student's point of view.

By coming to graduate school, a student has already made a strong commitment to developing a deep understanding of some particular subject. The student has to have been motivated as an undergraduate; he or she is not there merely to get a degree. After completing the PhD, that student intends to be a leader in teaching, research, and/or development.

In order to prepare a student to face the diverse world of chemical engineering, some improvements in the curriculum are necessary. I will focus on three important areas—they are related to each other in the sense that success in one depends on success in the other:

- **Teaching and Course Work**
- **Research**
- **Communication and Motivation Skills**

### **TEACHING AND COURSE WORK**

When I was an undergraduate, I participated in a debate on "education is what you remember, after you forget what you learned." It sounded odd at first, but I understood and supported it wholeheartedly later. University education teaches us many details (which most students forget as time goes by), but it is the basics (which are taught as a small fraction of the total duration) that must be retained. That we do not remember the details may not be a problem at all. In fact, the purpose of education is exactly what my debate topic was—to teach the "collective wis-

dom." However, many students do not realize this and lose their motivation, especially at the graduate level, when they take what they think are irrelevant classes. While it is clear that details are necessary in certain situations, it is important to recognize that the *collective wisdom* is what helps us in the long run.

If the above statements are valid for undergraduate education, they are even more pertinent at the graduate level. It is imperative that the graduate curriculum emphasize new and abstract ideas in diverse areas. I will expand on a couple of suggestions in the following sections.

### **Encourage Creativity in the Graduate Classroom**

There are two phases to any scientific idea: giving birth to a creative idea, and having the analytical ability to carry that idea to conclusion. Our education helps us to excel in the latter aspect, but not in the former. Some people even contend that creativity cannot be taught. While I cannot make a ruling on that, I do feel that it *can* be encouraged. In an article on graduate education, J. L. Duda<sup>[1]</sup> said, "...our educational system stifles creativity." We often see graduate classes where the student is asked to solve sophisticated versions of problems such as "given  $x$  and  $y$ , solve for  $z$ "—essentially similar to undergraduate classes. Such problems are illustrative in the short run, but do not help a lot in the long run.

Many students agree that the best thing (sometimes the only thing!) we remember from our undergraduate classes is the design project. However, most of us do not remember the details of Wei-Prater analysis. Why? Because the design project was open-ended and made us think about the practical aspects of what we learned, thus motivating us to understand and engrave it in our memory.

We should have at least a couple of classes in the graduate curriculum that are devoted to discussion of creative, open-ended problems. R. M. Felder<sup>[2]</sup> has had great success in such attempts in a graduate class. For example, he posed the problem, "You are faced with the task of measuring the volumetric flow rate of a liquid in a large pipeline. Come up with as many different ways to do the job as possible." There were some constraints<sup>[3]</sup> which I shall not list here, but he received two hundred different responses, illustrating that a seemingly straightforward question posed in an open way elucidates creative answers. It is not important that some of the responses were not commercially viable; what *is* important is that students were able to think creatively and to

apply their acquired knowledge to the problem. Since graduate students have already had the basic courses, the problems need not be confined to one subject, but can be open and general. They may include case studies, previously solved problems, and unsolved problems.

The advantage of such a class is that it encourages students to think creatively, it stimulates learning from others' lines of thought (and improving on them), and it brings various aspects of chemical engineering together in a classroom setting. Some

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***When I was an undergraduate, I participated in a debate on "education is what you remember, after you forget what you learned." It sounded odd at first, but I understood and supported it wholeheartedly later.***

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disadvantages could be that the students may be initially reluctant to participate because they are not used to such an approach (Professor Felder states, "...with a little practice the students become very enthusiastic"), it may take some time for faculty to create the right set problems for the course, and the evaluation method is subjective. (The fact that the graduate class is small helps in this respect, and at any rate, grades are not supposed to be that critical in graduate school.)

### **Less Material, More Discussions**

Classes should be more like James Bond movies. There should be something in them for everyone. Involving students in active discussions is a must, but unfortunately, many classes are simply monologues. There is usually some level of student interest in every class, and it is important that all the students get something out of the class. Even basic things such as explaining the day's topic in the beginning and summarizing major points in the end will ensure that students leave the class with *some* newly gained knowledge. It might reduce the amount of material covered in class, but it would be worth it because students would retain more of what was taught.

### **RESEARCH**

These days one often hears of the importance of research with regard to on-the-job success. Upon graduation, the student is expected to come up with creative ideas, to write proposals, and to attract co-workers, among other things, and the first few ideas and proposals lay the foundation for his or her long-term survival. A badly written proposal in the

initial stages of a career can have drastic implications. Even though post-doctoral research provides time for working on these aspects of a career, it is better to begin at the graduate level where one has five years to learn and correct mistakes.

In most cases, a graduate student learns to take a single task to its conclusion while the research advisor dominates selection of the primary task itself. Efforts should be made to give the student practice in identifying new and important problems in multidisciplinary areas. This would provide students with the opportunity to test and use their creative skills. The following sections offer a few suggestions along this line.

#### ***Make Research Proposals Mandatory***

Two-time Nobel Laureate at Caltech, Professor Linus Pauling, once said, "The best way to come up with great ideas is to come up with many ideas and later eliminate the bad ones." Every student should be required to write at least two original research proposals and to present them to the PhD committee. This requirement already exists in some schools. It challenges students to think about completely new ideas in related areas and opens them up to many new possibilities. To gauge the student's improvement, the proposals should be presented one year apart—once in the third year and once in the fourth, for example.

The disadvantage, if any, of making proposals compulsory may be that it takes away from the student's available time during his 'prime' and might impede his research progress. However, it helps in the overall growth of the student, and that is, after all, the primary purpose of graduate education.

#### ***Involve Students in Proposal Writing***

It is common knowledge that the competition for research dollars is getting stiffer every year. This makes life for a new professor even tougher than it normally is. Graduate school could be a good starting point for training. If students are exposed to proposal writing, presentation, and potential funding agencies during the latter part of their PhD work, the experience will serve them immensely later on in their careers. While the ACS guide on proposal writing is helpful, real-life experience and examples are certainly more useful. In fact, it may also help the faculty since the students can critique technical content and improve the presentation to "outsiders." I understand that many faculty already do this.

#### ***Hold Student Seminars on Common Topics***

This does not refer to the usual group seminars which are held to discuss research progress. It refers

to seminars that could serve as vehicles for identifying good research. The emphasis should be on how to critically analyze a paper and to learn from its contents. The papers should be chosen such that they are either pioneering or classical, very good or very bad. In this way the salient features of ground-breaking research, good research, or bad research can be easily illustrated. A very good or very bad paper is like Madonna—it makes a statement and the point is easy to see. A just-okay paper is more like a politician—it is tough to learn anything quantitative from what it says. In order to add weight to the seminar and make it even more effective, it could involve only a small number of students. It might be more valuable to the students if it is offered toward the end of the first year or at the beginning of the second year when they are about to embark on their research projects. The meetings should be informal and should be filled with constructive discussions.

### **COMMUNICATION AND MOTIVATIONAL SKILLS**

Communication skills are important for everyone. However, special emphasis on communication and motivational skills should be a part of graduate school. While it is incorrect to generalize, it can be said that most graduate students are relatively reserved and introverted. In fact, that may be one of their strengths! But after graduating and becoming professors, they will have to deal on a day-to-day basis with students, faculty and industrial groups, and as leaders in industry, they will have to interact with coworkers and other research groups. A leader must be able to motivate coworkers in order to achieve the desired results. *The importance of communication and motivational skills for success in the real world cannot be overstated.* It is imperative to stress their importance in the graduate curriculum. The best method for achieving this may be hard to identify, but some possibilities would involve a class on communication as part of the curriculum (taught by a communications expert), periodic communication and motivational workshops (with case studies), and an elective class on "How to Teach."

### **CONCLUSIONS**

The growing diversity of chemical engineering demands constant readjustment of the graduate curriculum. In order to produce creative leaders who can survive the changing environment, I have suggested some curriculum improvements as seen from a student's perspective. I feel the most important aspect to be considered is to encourage creative thinking in teaching and research. In teaching, the value of discussion-filled, creative classes is stressed, and

in order to increase effectiveness in illustrating a concept, use of open-ended problems is suggested. In research, the requirement of original research proposals as part of the degree requirements and faculty-student interaction in proposal writing are additional suggestions for consideration. Efforts should be made to improve student communication and motivational skills since they play a vital role in later careers, whether in teaching or in industry.

### ACKNOWLEDGMENTS

The author wishes to thank Professor Richard Felder (North Carolina State University) for being the inspiration behind this paper. The comments and suggestions of Professor J.A. Kornfield (Caltech), Professor D. Kompala (Colorado), Jeff Moore (Caltech), and Rajesh Panchanathan (Caltech) are appreciated.

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## ChE book review

### MODELING WITH DIFFERENTIAL EQUATIONS IN CHEMICAL ENGINEERING

by Stanley M. Walas

Butterworth-Heinemann, Stoneham, MA; \$145, (1991)

#### Reviewed by

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Today there is a recognized need for teaching a course in mathematical methods to undergraduate chemical engineers, and several schools have begun offering such courses. But there are only a few textbooks available that are primarily addressed to chemical engineering students. This book by Walas is therefore a very timely addition to the literature. It is an excellent book.

The book consists of fifteen chapters and an appendix. Chapters 1 to 7 focus on mathematical methods of solutions of ordinary and partial differential equations. Integral equations are briefly treated in Chapter 6. Theoretical discussions, such as existence and uniqueness of solutions, have been skipped

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and instead, emphasis has been placed on solution techniques and detailed applications. All classical methods of solution are covered in detail. Numerical and approximate methods are emphasized early on throughout the presentation. The material is well presented, and a wealth of references for further reading are provided. These chapters give the student a good background in the different methods (analytical, numerical, and approximate) for solving ODEs and PDEs. Limitations of the techniques are clearly explained, and methods for overcoming the difficulties are presented.

After the mathematics of differential equations has been presented, there is a chapter devoted to the principles of the mathematical formulation of engineering processes. What follows next is the distinctive part of this book—the derivations and solutions of differential equations of some of the major disciplines of chemical engineering. The topics covered include thermodynamics, mass transfer, fluid flow, heat transfer, chemical reactions and reactor design, and process control. Attention is restricted primarily to the differential equations that occur in these processes. Many of the topics are reinforced by mathematical or numerical examples as well as problems for the reader, most of them with answers provided.

Throughout the book the author guides the reader toward more comprehensive sources of information, and the reference list is excellent and up to date. Little mathematics beyond calculus is expected of the reader. Computer usage by the examples and problems is restricted to readily available user-friendly PC diskettes. The treatment of most topics is fairly complete, and beginning students will not need to relearn the material as their sophistication advances.

Overall, this book will satisfy the demands of undergraduate and first-year graduate chemical engineering students who usually have difficulty in understanding the presentations in more general mathematics texts. The book may also be of value to those who have already mastered the typical chemical engineering curriculum, *e.g.*, the chemical engineering practitioner, and who are now involved in some aspect of computational or mathematical modeling of chemical engineering processes.

In summary, this is a highly recommendable textbook for senior and beginning graduate students, set apart by an easy style, a healthy amount of exercises, lots of references, and a wide coverage of topics. The author is to be commended for his excellent effort and contribution to the chemical engineering literature. □

# PATTERN FORMATION IN CONVECTIVE-DIFFUSIVE TRANSPORT WITH REACTION

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It has long been recognized in the chemical engineering profession and in the physical and chemical sciences that material and energy transport play a central role in both the processing of materials and in chemical reactor performance. Much of the theoretical and numerical modeling efforts for transport and reaction, however, has traditionally been restricted to linearized models (*e.g.*, linear rates of reactions, linear irreversible thermodynamics for transport and dissipation, and neglecting convection as a source of nonlinearity).

It is now clear that approaches solely based on linear theories fail to describe many interesting properties of these systems; namely, spatial and temporal organization, the formation of patterns, and the existence of time-dependent, aperiodic states. In fact, the field of nonlinear dynamics (which encompasses a variety of distinct disciplines) has emerged as a

coherent subfield of science in the last decade. In the field of chemical engineering, pioneering efforts in the study of strongly nonlinear reaction-diffusion systems have been pursued by Amundson, Aris, and collaborators.<sup>[1,2]</sup>

In general, when a system that is initially placed in a state of thermodynamic equilibrium is forced (and sometimes maintained) away from that state, its evolution can lead to a rich variety of phenomena, quite distinct from systems that are in, or close to, equilibrium. In some cases the system goes through a number of instabilities that lead to chaotic behavior. In others the evolution is through a succession of spatiotemporal patterns that may lead to complicated, albeit stationary, structures.

From a fundamental point of view, the common feature of all these systems is the essential role played by the nonlinearities in the relevant equations of the models. In most cases, the nonlinearities cannot be studied as perturbations around some well-characterized state, but rather they lead to qualitatively different behavior.

Our research focuses on several complementary aspects of problems that encompass convective-diffusive transport (with and without chemical reactions) in a variety of applications of current interest in chemical engineering. Four main areas of research will be reviewed here: 1) chemical and catalytic reacting systems, 2) biological and biochemical interacting systems, 3) convective instabilities in fluids and liquid crystals, and 4) crystal growth from the melt. They share a common methodology based on nonlinear dynamics, but since a general formulation (let alone a general solution) to all of the problems is out of the question at the present time, each research area focuses on the most relevant mechanisms and nonlinearities for the case at hand.

For example, the study of chemical and catalytic reacting systems is conducted in one spatial dimension and with considerably simplified convection. In the study of convective instabilities, only convective and diffusive transport is considered. In the latter case the system is also kept not too far above the



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**Jorge Viñals** received his BS in Physics at the University de Barcelona, Spain (1981) and his PhD in Physics-Material Science at the same university in 1983. His main areas of research are in kinetics of first-order transitions, morphological stability and crystal growth, and pattern formation in convective instabilities.

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threshold for the primary convective instability so that the emerging patterns are relatively simple (away from a turbulent state). The study of crystal growth from the melt allows for moving boundaries of arbitrary shape separating the various phases, but neglects convection.

The main goals of the research in all cases are characterization of all possible stationary states of the system (uniform and, more importantly, states which are non-uniform in space), determination of the stability of these stationary states when the parameters that can be controlled experimentally are changed (*e.g.*, the composition of the reactants and the temperature of the reactor), and the calculation of the transient evolution between these stationary states.

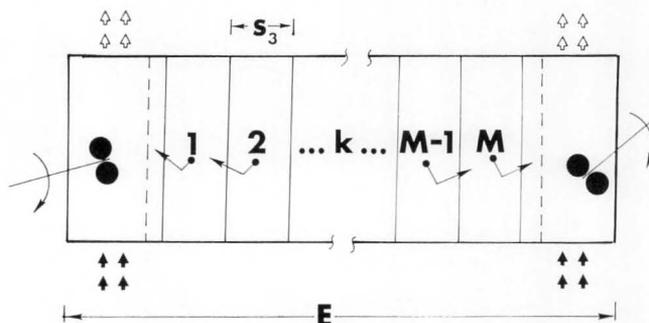
### HIERARCHICAL APPROACH FOR INTERACTIONS IN CHEMICAL, BIOCHEMICAL, AND BIOLOGICAL SYSTEMS

The overall objective of this part of our research is to investigate the chemical, biological, and biochemical structures and functions that arise from the reaction, diffusion, and convection of molecular species. The emphasis is on applying operator-theoretic techniques and inverse integral formulations to analyze the dynamics of transport and reaction problems with multicomponents and in multidimensional domains of hierarchical structure (shown, for example, schematically in Figure 1). Furthermore, the analysis is aided by group-theoretic methods<sup>[3]</sup> and simulations performed in conventional and parallel supercomputers. A very wide range of naturally occurring or synthetically constructed chemical, biological, and biochemical phenomena can be studied within the framework of reaction and convective-diffusive transport.

Direct interactions result from the diffusive or convective coupling through adjoining boundaries between macromolecules, catalyst particles, organelles, and cells. Indirect interactions refer to interactions mediated by intervening fluid regions. Within the framework of the direct and indirect interactions, we seek to analyze the dynamic behavior of heterogeneous populations of macromolecules, catalyst particles, organelles, cells, and multicellular organisms from a hierarchical point of view.

In this hierarchical approach, a domain (*e.g.*, a population of cells or organelles) is considered in terms of sub-domains (*e.g.*, organelles or macromolecules) and the mathematical description accounts for the transport and reaction processes that occur inside these domains, as well as for those occurring

***It is now clear that approaches solely based on linear theories fail to describe many interesting properties of these systems; namely, spatial and temporal organization, the formation of patterns, and the existence of time-dependent, aperiodic states.***



**Figure 1.** A single domain (which could itself be a subdomain of a larger domain), showing  $M$  subdivisions or layers such as the ones discussed in the text, and that corresponds to the model given in Eq. (1).

between the domains throughout the environmental media. This hierarchical description features an assemblage (or superstructure) based on units of "smaller" dimensions which may, in turn, display different degrees (or levels) of description.

This approach (although not entirely new) has not previously been fully exploited to describe the dynamics of biological and biochemical systems. Past efforts have focussed almost completely on extending the Rashevsky-Turing<sup>[4,5]</sup> ideas to a variety of situations, but have failed to account for the indirect interactions which have been shown to be as important as the Rashevsky-Turing interactions in generating a rich variety of behaviors in catalytic reactors.<sup>[6]</sup> Our research aims at elucidating the roles of both types of interactions.

The operator-theoretic technique allows a full characterization of the dynamic behavior of systems without the complete numerical solution to the governing differential models. This also allows for a coupling of different levels of information in a given system and thus leads to the analysis of the composite system in terms of the simpler systems. Furthermore, the inverse integral formulation allows for a very efficient numerical strategy to solve the complete nonlinear differential model using information provided by the operator formulation.

### **Chemical and Catalytic Reacting Systems**

The field of pattern formation in catalytic reactors has been reviewed recently in the framework of di-

rect and indirect interactions.<sup>[7]</sup> The analysis addresses a wide variety of aspects, including the introduction of a hierarchy of reactor models, mathematical techniques, previous work done in the field, and important problems to be investigated in future research efforts.

**Direct Interactions** • Recently, Locke and Arce<sup>[8,13]</sup> have considered one-dimensional diffusion, reaction, and convection in a system of M-layers where the diffusion coefficients, the phase distribution coefficients, reaction rate constants, and convective transport coefficients were allowed to vary from one layer to the next. Coupling between the layers was modeled through equilibrium and flux boundary conditions, where the flux condition included both convection and diffusion. For one-dimensional transport which may include electrophoretic transport in rectangular coordinates, the general molar species continuity equation for the m<sup>th</sup> layer is

$$\frac{\partial c_m}{\partial t} = -u_m \left(\frac{V}{L}\right)_m \frac{\partial c_m}{\partial x} + D_m \frac{\partial^2 c_m}{\partial x^2} + k_m f_m(c_m) \quad (1)$$

where

- c = cross sectional area average molar species concentration
- (V/L) = applied voltage per unit length
- u = electrophoretic mobility
- k = reaction rate constant
- D = diffusion coefficient
- f = function that contains the concentration and spatial variations of the reaction rate.

In the above model formulation, each layer is assumed to be a different phase, and therefore flux and equilibrium boundary conditions are required at the M - 1 interfaces. A general approach would require the addition of a material balance over well-mixed external regions in analogy with the approach of Ramkrishna and Amundson<sup>[9-11]</sup> and Parulekar and Ramkrishna.<sup>[12]</sup> This would give

$$V_0 \frac{dc_0}{dt} = c_{0f} F_0 - c_0 F_0 + a \left[ D_1 \left( \frac{\partial c_1}{\partial x} \right)_{x=0^+} - u_1 \left( \frac{V}{L} \right)_1 c_1(x=0^+) \right] \quad (2)$$

$$V_L \frac{dc_L}{dt} = c_{Lf} F_L - c_L F_L - a \left[ D_M \left( \frac{\partial c_M}{\partial x} \right)_{x=L^-} - u_M \left( \frac{V}{L} \right)_M c_M(x=L^-) \right] \quad (3)$$

where

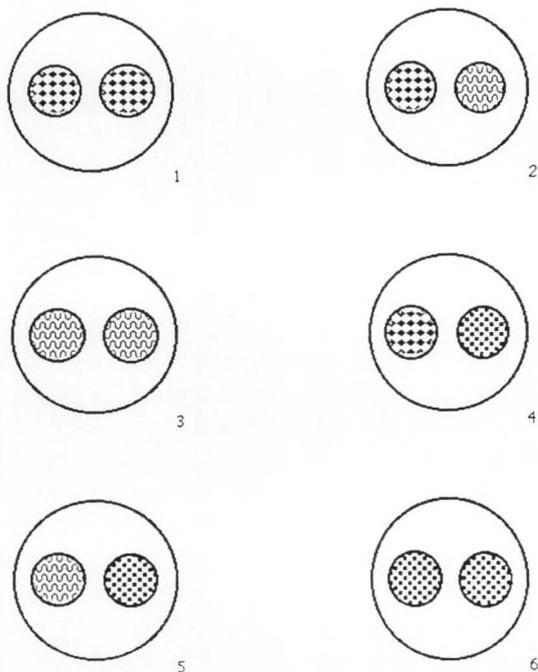
- V = volume
- c = molar concentration
- F = volumetric flow into the mixed cells
- a = cross sectional area of the membrane surfaces

The subscripts 0 and L represent the two well-mixed external regions, and f represents the feed streams into the two external regions (shown schematically in Figure 1).

The interactions between the different layers in this model can be considered to be direct interactions since the layers are physically and geometrically coupled at their (phase) boundaries. This is in contrast to coupling through indirect interactions that rely on an intermediate phase, such as a bulk fluid, to mediate the interactions between the two systems not physically adjacent. The model described here may be viewed as a prototype to investigate the behavior of cells immersed in a fluid environment. The system will feature an assemblage of domains as shown in Figure 1. The solution to the above models is being undertaken by using operator-theoretic methods.<sup>[8-13]</sup> Current work is concerned with performing linear stability analysis for the case of reacting systems coupled with hydrodynamic and electrophoretic transport and diffusion.

**Indirect Interactions** • In a series of recent studies, Arce and Ramkrishna<sup>[6,7,14]</sup> and Ramkrishna and Arce<sup>[15-17]</sup> considered transport and reaction problems in catalytic reactors. This research has shown that indirect interactions are as important as the direct interactions in producing a wide variety of very interesting steady state and dynamic behaviors in catalytic reacting systems. Moreover, assemblies of catalyst particles showing only interactions mediated by the fluid medium are able to display a broader class of collaborative phenomena (*i.e.*, behaviors caused by the mutual interactions among the particles) than those found in assemblies showing only direct interactions. Assemblages of catalyst particles with only indirect interactions<sup>[6,7]</sup> have uniform steady states that can show collaborative multiplicity and collaborative reversal of instability before breaking the symmetry. This allows the particle to preserve, partially, the stability inside the reactor. Pattern formation is displayed when the assembly of catalyst particles breaks the symmetry of the uniform steady state (see Figure 2).

Collaborative multiplicity and collaborative reversal of stability can also be observed in patterns; however, it is impossible for the assembly to show collaborative reversal of stability. The mathematical analysis that is used to study this multitude of phenomena is based on a theory that exploits the complete understanding of the isolated particle (or cell) in an operator-theoretic framework. Furthermore, the analysis has been pursued further by using sin-



**Figure 2.** Pattern formation in a well-mixed system showing two individual interacting catalytic particles or cells. Configurations 2, 4, and 5 clearly show the cells in two different steady states. Different steady states inside each cell are schematically depicted with different patterns.

gularity theory and group-operator methods.<sup>[18]</sup> In addition, the investigation has been extended to catalytic packed-bed reactors<sup>[16]</sup> where indirect interactions among particles (with internal diffusion) are accounted for in an axial diffusive convective fluid.

This investigation is very relevant for describing the behavior of assemblies (or superstructures) of cells in terms of smaller domains (or units). These computations, which include the determination of regions of different behaviors in the parameter space and the identification of all the steady states, can be efficiently performed using an inverse integral formulation.<sup>[19]</sup> This inverse integral formulation uses a non-linear integral operator of the Hammerstein-Volterra type with a kernel given by the Green function of the differential problem. The Green function can be computed in terms of the eigenvalues and eigenvectors of the differential linear (transport) operator without the reaction terms. This approach greatly simplifies the computations of steady states for different kinds of non-linear sources. Furthermore, the integral formulation is very suitable for implementation by parallel computer architectures and, therefore, the process of obtaining steady states from complex assemblages composed of several units (cells) can be greatly accelerated.

### Biological and Biochemical Interacting Systems

Rapid advances in molecular and cellular biology over the last ten to twenty years have inspired research efforts in the development of molecular and metabolic engineering. In order to advance our abilities to create artificial systems through molecular and metabolic engineering, it is necessary to have a full understanding of the fundamental dynamics of living systems. Dynamical aspects of living systems include subcellular enzymatic reactions for cell growth and reproduction, enzymatic and genetic-level control processes, supracellular morphological development, cell cycles, and evolutionary processes. In addition to developing an understanding of how each separate level of process works, it is necessary to integrate different levels of structure into an overall framework that describes the interactions between these different levels.

The interplay of convective-diffusive transport with reaction yields a wide variety of steady-state and dynamic behavior in biochemical and biological systems. This includes oscillations, wave propagation, multiplicity of uniform stationary states, and (temporal and spatial) pattern formation. Oscillations occur in enzyme reactions, protein synthesis, cell cycles, muscle contraction, and many other cellular and physiological processes.<sup>[20]</sup> Oscillations in the glycolytic pathway have been extensively studied both experimentally and theoretically. Most of the efforts in the literature have been devoted primarily to temporal variations and to the determination of stability conditions for non-linear chemical reactions with several components.<sup>[20,21]</sup> Generally, in isothermal systems, it is necessary for the chemical reactions to exhibit non-linear kinetics in order for temporal patterns to occur. Higgens<sup>[22]</sup> considered the general types of autocatalytic chemical reactions with positive or negative feedback that give rise to oscillatory variations of species concentrations. Some very current applications of temporal pattern formation involves modeling cell cycles via the recently determined key metabolic component cyclin.<sup>[23]</sup>

Temporal variation alone, however, since it neglects all geometrical and spatial structure, cannot describe systems where spatial structure is important. Reaction/diffusion problems have been used to consider problems in biological morphological development, biochemical reactions, and population ecology since the ideas introduced by Rashevsky<sup>[4,24]</sup> and Turing.<sup>[5]</sup> Turing considered reaction and diffusion in a two-component and one-dimensional system.

Scriven and coworkers<sup>[25,26]</sup> have developed a general analysis of multicomponent reaction and diffu-

sion in a single region coupled to other regions through indirect transfer expressions.

A large number of phenomena have subsequently been investigated from the perspective<sup>[20,27]</sup> of reaction and diffusion within a single phase. What remains to be considered is a comprehensive approach to include systems of multicomponents in multiphase domains and a hierarchy of both direct and indirect interactions. The main goal of our research is the development of such a comprehensive approach.

Biological and biochemical systems can be broken down into a number of functional and structural units (*e.g.*, macromolecules, organelles, cells, tissues, populations, and communities). These units can in turn interact through direct or indirect means in analogy to the chemical reactor and separation models given above. Martin, *et al.*,<sup>[28]</sup> have formulated a one-dimensional multiple layer diffusion and convection model for the transport of auxin, a plant hormone, up the stem of a plant. Their model is simpler than the one considered above by Locke and Arce<sup>[8,13]</sup> and they have solved it using the cumbersome method of Laplace transform. This methodology gives no indication of the role of the different parameters on the dynamics of the process.

From a more general perspective, Almirantis and Papageorgiou<sup>[29]</sup> have considered reaction boundary coupling between multiple layers in a one-dimensional system as a model of intercellular communication. They developed a stability analysis to determine the conditions for pattern formation. Operator theoretic methods can give a much clearer view of the stability criteria through an analysis of the spectrum of the operators. Currently, several geometrical configurations of cell systems are being investigated to determine their steady-state structure, linear stability, and pattern formation characteristics.

## CONVECTIVE INSTABILITIES IN FLUIDS AND LIQUID CRYSTALS

The Rayleigh-Bénard instability in simple fluids is a classical fluid instability that has been well characterized both theoretically and experimentally, at least when the Rayleigh number is not too far from the critical Rayleigh number and the aspect ratio of the experimental cell is not too large.<sup>[30,31]</sup> Under these conditions, when the system is brought above threshold, a convective instability occurs and the familiar pattern of convective rolls appears.

Although this is a simplified situation, it is very important in our understanding of nonlinear phenomena because the equations describing the sys-

tem are well known and the fluid parameters that appear in them can be measured with sufficient accuracy. Furthermore, experiments can be conducted under well controlled conditions. It therefore provides a good testing ground for many of the ideas of pattern formation in nonlinear systems and an opportunity for detailed and precise comparisons between the predictions given by well defined models and the experiments.

Unfortunately, for most commonly studied fluids the parameters of the fluid are such that systems comprising only a few convective rolls can be studied under normal laboratory conditions. The emerging structures are therefore greatly influenced by the geometry and size of the experimental cell. More recently, however, experiments have been conducted on gases<sup>[32]</sup> or on the electro-hydrodynamic instability in nematic liquid crystals.<sup>[33]</sup> The scale of the convective rolls in these cases is much smaller than the size of the cell and the issues discussed above are beginning to be studied in greater detail.

We have concentrated on the analysis of the stochastic Swift-Hohenberg equation.<sup>[34]</sup> This equation describes the evolution of a scalar field, function of position  $\vec{r}$  and time  $t$ , that can be written in dimensionless form as

$$\frac{\partial \psi(\vec{r}, t)}{\partial t} = \left[ \varepsilon - (\nabla^2 + 1)^2 \right] \psi - \psi^3 + \xi(\vec{r}, t) \quad (4)$$

The quantity  $\varepsilon$  acts as control parameter. From  $\varepsilon < 0$  the solution  $y = 0$  is linearly stable, whereas at  $\varepsilon = 0$  it becomes unstable to periodic solutions. The stochastic function,  $\xi(\vec{r}, t)$ , is normally assumed to be gaussian distributed and delta-correlated. This equation has been shown to be equivalent in the long-wavelength, long-time limit the Boussinesq approximation to the hydrodynamic equations that described convection in a simple fluid close to the convective instability. In that case, the stochastic contribution is related to the underlying thermal fluctuations in the fluid. More generally, this equation can be considered as a generic model that describes the formation of spatially periodic structures.

Three main issues are investigated. First, the question of pattern selection, namely which, out of the infinitely many linearly stable stationary states, is dynamically selected from typical initial conditions. Second, convective patterns are effectively one- or two-dimensional. Fluctuations might be expected to destroy the long-range order implicit in the convective pattern. The third issue is the transient dynamics of roll formation. Eq. (4) has been solved numerically on the Connection Machine 2 at SCRI. The

aspect ratio of the systems studied ranges in the hundreds (*i.e.*, several hundred convective rolls), much larger than systems that are experimentally feasible in simple fluids. As discussed above, recent experiments in nematic liquid crystals are beginning to be able to measure thermal fluctuations and to study ratios comparable to the sizes that we have used in our solutions. We expect that our predictions will be tested in these latter systems.

Figure 3 shows an example of our results<sup>[35]</sup> with the various structures of the stationary solutions. The configurations shown are typical examples of stationary solutions obtained numerically (only a portion of the system size studied is shown for clarity). At zero amplitude of the fluctuations,  $F' = 0$  (states labeled smectic), configurations of rolls possess both positional and orientational long-range order. At low values of  $F'$  (states labeled nematic) orientational correlations are long-ranged but the system is positionally disordered. Above the solid line in the figure, the pattern is completely disordered. The location of the solid line in the figure has been found numerically for one value of  $\varepsilon$ . A theoretical analysis that we have developed predicts that it is given by  $F' \propto \varepsilon$ , which is what is plotted in the figure.

Work is now in progress to explore more complex situations with convection in non-Boussinesq sys-

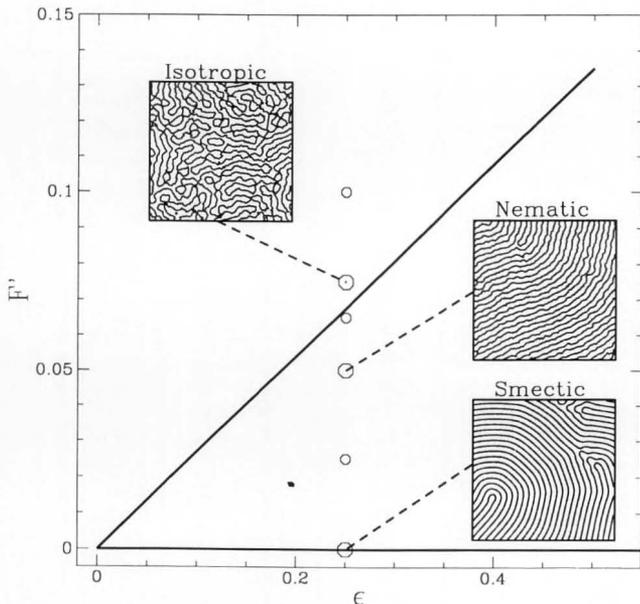
tems, the decay of a long-wavelength instability of periodic patterns known as the Eckhaus instability, extensions to non-gradient systems, etc. The combination of experimental work and detailed numerical solutions to model systems is providing a number of very interesting results on the pattern forming properties of systems that are far from thermodynamic equilibrium.

## CRYSTAL GROWTH FROM THE MELT

Crystal growth is but one example in the study of the evolution of the shape of the interfaces that separate domains of various phases during a phase transformation. Although this is one of the most studied examples, the same phenomenology also occurs in all phase transformations in which diffusive transport plays a dominant role in controlling the transformation rate (*i.e.*, diffusion of heat or of some chemical species). Examples are numerous, including the growth of semiconductor crystals from the melt, metal alloy casting, and the growth of protein crystals.

In the more general formulation, one is confronted with a nonlinear free boundary problem for which analytic solutions are rare.<sup>[36]</sup> Even in the simpler case in which convective motion in the fluid phase is neglected, limited progress has been achieved in determining stable propagating solutions of the front that separates the different phases. A great deal is known about the existence of steady states and about their stability in systems that undergo some type or morphological instability to a finger-like or cellular structure.<sup>[37]</sup> These studies have focused on models of directional or dendritic solidification of single component or multicomponent systems and models of viscous fingering in fluids. Intricate asymptotic analyses have yielded the stationary solutions of various models and, in some cases, the stability condition of such solutions to infinitesimal perturbations.

The approach that we have taken involves recasting the partial differential equations that describe mass diffusion in the phases and the appropriate boundary conditions on the moving interface, by an integrodifferential equation involving the coordinates of the interface alone, or "interface equation."<sup>[38,39]</sup> This is accomplished by the introduction of the Green function for the diffusion operator in the various phases. The interface equation is then solved as an initial value problem for a given initial position of the interface. Studies to date have focused on the analysis of the evolution of the interface shape following the instability of a planar front. Recent studies by us and others<sup>[39,40]</sup> are focusing on the tran-



**Figure 3.** Portions of typical configurations obtained as stationary solutions of Eq. (4). The configurations labeled isotropic, nematic, and smectic correspond to intensities of the fluctuations  $F' = 0.075, 0.05,$  and  $0,$  respectively. In all these plots the lines drawn are the lines of  $\psi(\vec{r}) = 0.$

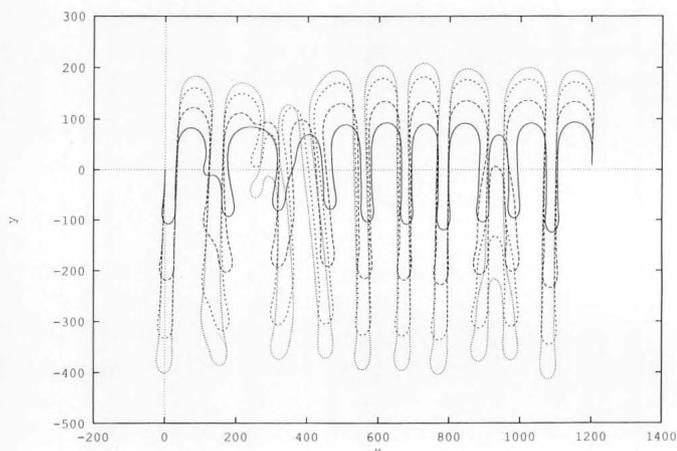
sient dynamics of formation of periodic cellular structures (an example of such evolution is shown in Figure 4). Numerical studies reveal the existence of conventional stationary states in addition to traveling wave states or even chaotic structures. This rich behavior can be observed within a surprisingly narrow range of material and control parameters.

## CONCLUSION

We have summarized a variety of problems concerning instabilities and the formation of patterns in convective-diffusive systems, with or without chemical reactions, that are being addressed in the chemical engineering department at FAMU/FSU. We focus our attention on novel mathematical approaches that combine analytical techniques and numerical work performed on conventional and parallel supercomputers. The analytic techniques center around operator-theoretic, group-theoretic, and Green function methods to study a variety of nonlinear processes in chemical and catalytic reacting systems, and pattern-forming instabilities in fluids and crystal growth. These methods allow the implementation of powerful numerical algorithms on vector and massively parallel supercomputers, such as those presently available at Florida State University.

## ACKNOWLEDGMENT

Part of this work has been conducted in collaboration with other colleagues and former academic advisors. It is a pleasure to acknowledge K. Elder, D. Jasnow, M. Grant, H. Irazoqui, and D. Ramkrishna for very fruitful collaborations. One of us (PA) wants to thank Professor R.G. Carbonell for very interesting discussions and observations. PA and BL ac-



**Figure 4.** Example of the temporal evolution of an interfacial pattern separating the solid and fluid phases during directional solidification. The lines shown are different times following the instability of a planar front.

knowledge support from NASA-TRDA-204 and the FAMU/FSU College of Engineering. JV is supported by the Microgravity Science and Applications Division of the NASA under contract No. NAG3-1284 and by the Supercomputer Computations Research Institute, which is partially funded by the U.S. Department of Energy Contract No. DE-FC05-85ER25000.

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## NEURAL NETWORKS

*Continued from page 179.*

obtain the correct ordering for both the manipulated and the controlled variables, the engineer requires a great deal of process understanding.

An alternative methodology under study in the IPS Lab is very ambitious in that it seeks to pose the multivariable control design with objective prioritization as a multilevel optimization problem with binary variables. Binary variables can be visualized as on-off keys that switch controller and economic objectives and constraints on or off as appropriate to achieve the desired prioritization.

## FUTURE DIRECTIONS

As our research in neural networks, optimization, and process control matures, the focus in the IPS Lab is shifting to demonstration of the methods in collaboration with local industry. One project has begun which seeks to use neural network-based methods for controlling the quality of parts produced from an injection molding process. A second project is employing similar methods for controlling the incineration of hazardous wastes. A third effort is exploring the use of neural networks for optimizing the efficiency of combustion of pulverized coal.

Such real-world implementations are important in process control research. When developments are restricted to simulated processes, the complete process character can be specified by the same researcher

who is responsible for the control system developments. Real plants, on the other hand, have a process character that is specified by nature, thereby truly testing the effectiveness of new developments.

Perhaps the most important aspect, however, is that real-world demonstrations permit developments to be tested by the ultimate user of the technology—the industrial practitioner. It is only when the technology is in the practitioner's hands that laboratory developments receive the critical evaluations which help guide subsequent improvements and refinements, and define new avenues for fruitful research.

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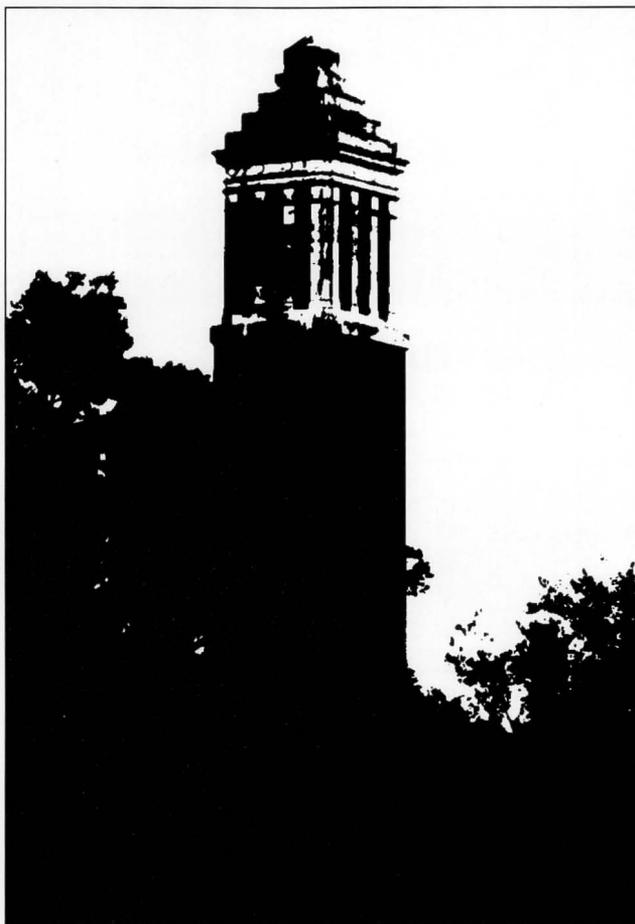
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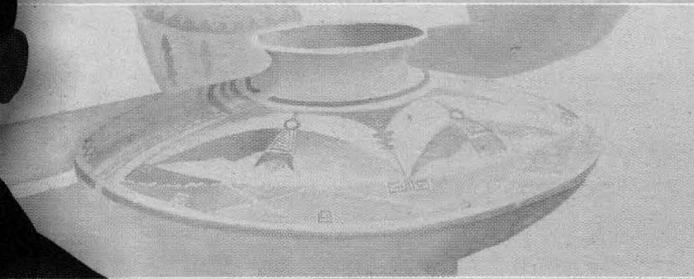
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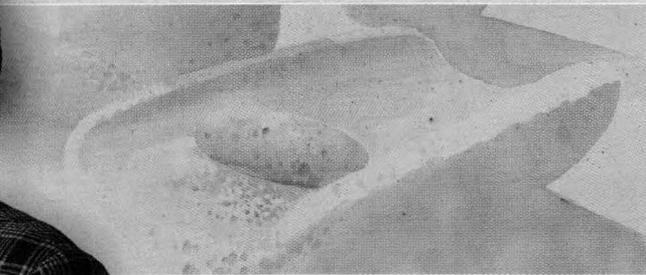
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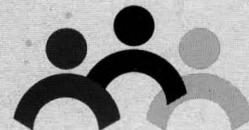
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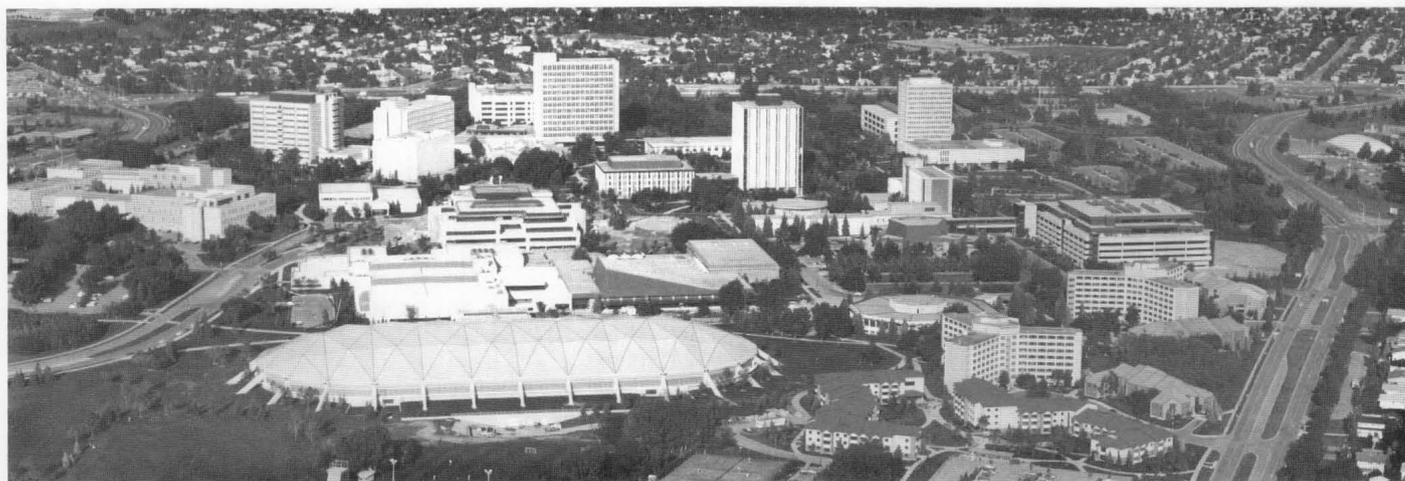
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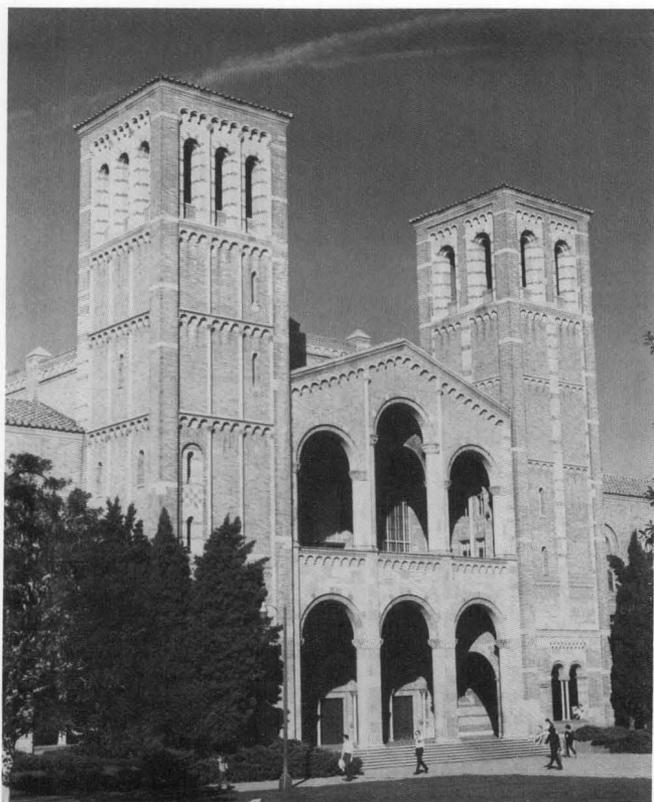
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Kinetics, Combustion, and Catalysis  
Semiconductor Device Chemistry and Surface Science  
Electrochemistry and Corrosion  
Biochemical and Biomedical Engineering  
Aerosol Science and Technology  
Air Pollution Control and Environmental Engineering

## CONTACT

Admissions Officer  
Chemical Engineering Department  
5531 Boelter Hall  
UCLA  
Los Angeles, CA 90024-1592  
(310) 825-9063

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## • FACULTY AND RESEARCH INTERESTS •

- L. GARY LEAL** Ph.D. (*Stanford*) • (Chairman) • Fluid Mechanics; Transport Phenomena; Polymer Physics.
- ERAY S. AYDIL** Ph.D. (*University of Houston*) • Microelectronics Materials Processing
- SANJOY BANERJEE** Ph.D. (*Waterloo*) • Two-Phase Flow, Chemical & Nuclear Safety, Computational Fluid Dynamics, Turbulence.
- BRADLEY F. CHMELKA** Ph.D. (*U.C. Berkeley*) • Guest/Host Interactions in Molecular Sieves, Dispersal of Metals in Oxide Catalysts, Molecular Structure and Dynamics in Polymeric Solids, Properties of Partially Ordered Materials, Solid-State NMR Spectroscopy.
- HENRI FENECH** Ph.D. (*M.I.T.*) (Professor Emeritus) • Nuclear Systems Design and Safety, Nuclear Fuel Cycles, Two-Phase Flow, Heat Transfer.
- GLENN H. FREDRICKSON** Ph.D. (*Stanford*) • Electronic Transport, Glasses, Polymers, Composites, Phase Separation.
- OWEN T. HANNA** Ph.D. (*Purdue*) • Theoretical Methods, Chemical Reactor Analysis, Transport Phenomena.
- JACOB ISRAELACHVILI** Ph.D. (*Cambridge*) • Surface and Interfacial Phenomena, Adhesion, Colloidal Systems, Surface Forces.
- FRED F. LANGE** Ph.D. (*Penn State*) • Powder Processing of Composite Ceramics; Liquid Precursors for Ceramics; Superconducting Oxides.
- GLENN E. LUCAS** Ph.D. (*M.I.T.*) • (Vice Chairman) • Radiation Damage, Mechanics of Materials.
- ERIC McFARLAND** Ph.D. (*M.I.T.*) M.D. (*Harvard*) • Biomedical Engineering, NMR and Neutron Imaging, Transport Phenomena in Complex Liquids, Radiation Interactions.
- DUNCAN A. MELLICHAMP** Ph.D. (*Purdue*) • Computer Control, Process Dynamics, Real-Time Computing.
- JOHN E. MYERS** Ph.D. (*Michigan*) (Professor Emeritus) • Boiling Heat Transfer.
- G. ROBERT ODETE** Ph.D. (*M.I.T.*) • Radiation Effects in Solids, Energy Related Materials Development
- DALE S. PEARSON** Ph.D. (*Northwestern*) • Rheological and Optical Properties of Polymer Liquids and Colloidal Dispersions.
- PHILIP ALAN PINCUS** Ph.D. (*U.C. Berkeley*) • Theory of Surfactant Aggregates, Colloid Systems.
- A. EDWARD PROFIO** Ph.D. (*M.I.T.*) • Biomedical Engineering, Reactor Physics, Radiation Transport Analysis.
- ROBERT G. RINKER** Ph.D. (*Caltech*) • Chemical Reactor Design, Catalysis, Energy Conversion, Air Pollution.
- ORVILLE C. SANDALL** Ph.D. (*U.C. Berkeley*) • Transport Phenomena, Separation Processes.
- DALE E. SEBORG** Ph.D. (*Princeton*) • Process Control, Computer Control, Process Identification.
- PAUL SMITH** Ph.D. (*State University of Groningen, Netherlands*) • High Performance Fibers; Processing of Conducting Polymers; Polymer Processing.
- T. G. THEOFANOUS** Ph.D. (*Minnesota*) • Nuclear and Chemical Plant Safety, Multiphase Flow, Thermohydraulics.
- W. HENRY WEINBERG** Ph.D. (*U.C. Berkeley*) • Surface Chemistry; Heterogeneous Catalysis; Electronic Materials
- JOSEPH A. N. ZASADZINSKI** Ph.D. (*Minnesota*) • Surface and Interfacial Phenomena, Structure of Microemulsions.

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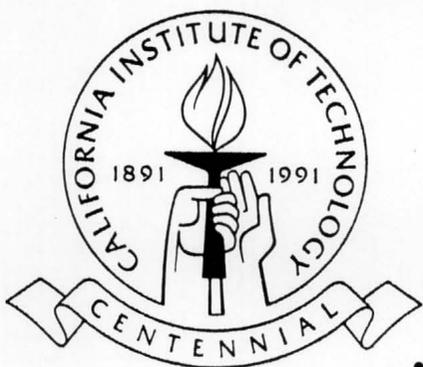
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*Julia A. Kornfield*  
*Manfred Morari*  
*C. Dwight Prater (Visiting)*  
*John H. Seinfeld*  
*Nicholas W. Tschoegl (Emeritus)*  
*Zhen-Gang Wang*

RESEARCH INTERESTS

*Aerosol Science*  
*Applied Mathematics*  
*Atmospheric Chemistry and Physics*  
*Biocatalysis and Bioreactor Engineering*  
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*Chemical Vapor Deposition*  
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*Microelectronics Processing*  
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Professor Mark E. Davis  
Department of Chemical Engineering  
California Institute of Technology  
Pasadena, California 91125

## Clues

**John L. Anderson**

Membrane and colloid transport phenomena

**Lorenz T. Biegler**

Process simulation and optimization

**Paul A. DiMilla**

Cellular and biomolecular engineering; cell membranes

**Michael M. Domach**

Biochemical engineering and cell biology

**Ignacio E. Grossmann**

Batch process synthesis and design

**William S. Hammack**

Characterization of amorphous materials; pressure-induced amorphization

**Annette M. Jacobson**

Solubilization and surfactant adsorption phenomena

**Myung S. Jhon**

Magnetic and magneto-optical recording

**Edmond I. Ko**

Chemistry of solid-state materials; semiconductor processing

**Gary J. Powers**

Decision-making in the design of chemical processing systems

**Dennis C. Prieve**

Transport phenomena and colloids, especially electrokinetic phenomena

**Jennifer L. Sinclair**

Multiphase flow

**Paul J. Sides**

Electrochemical engineering; growth of advanced materials

**Robert D. Tilton**

Biomolecules at interfaces

**Herbert L. Toor**

Transport phenomena; energy utilization and transformation

**Arthur W. Westerberg**

Engineering design

**B. Erik Ydstie**

Process Control



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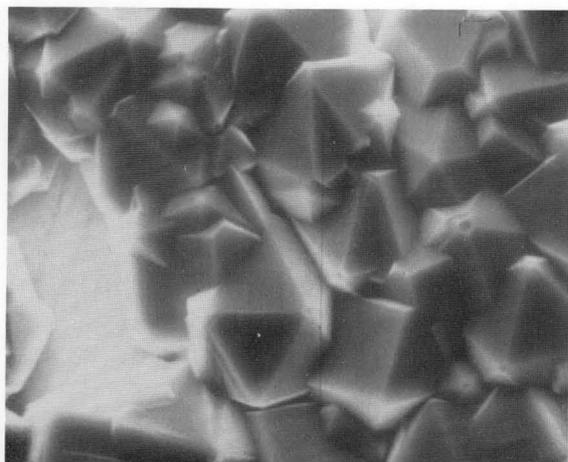
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The Graduate Coordinator  
Department of Chemical Engineering  
Case Western Reserve University  
Cleveland, Ohio 44106

---

### Faculty and Specializations

---

**John C. Angus**, Ph.D. 1960, University of Michigan  
*Redox equilibria, diamond and diamond-like films, modulated electroplating*

**Coleman B. Brosilow**, Ph.D. 1962, Polytechnic Institute of Brooklyn  
*Adaptive inferential control, multi-variable control, coordination algorithms*

**Robert V. Edwards**, Ph.D. 1968, Johns Hopkins University  
*Laser anemometry, mathematical modeling, data acquisition*

**Donald L. Feke**, Ph.D. 1981, Princeton University  
*Colloidal phenomena, ceramic dispersions, fine-particle processing*

**Nelson C. Gardner**, Ph.D. 1966, Iowa State University  
*High-gravity separations, sulfur removal processes*

**Uziel Landau**, Ph.D. 1975, University of California (Berkeley)  
*Electrochemical engineering, current distributions, electro-deposition*

**Chung-Chiun Liu**, Ph.D. 1968, Case Western Reserve University  
*Electrochemical sensors, electrochemical synthesis, electro-chemistry related to electronic materials*

**J. Adin Mann, Jr.**, Ph.D. 1962, Iowa State University  
*Interfacial structure and dynamics, light scattering, Langmuir-Blodgett films, stochastic processes*

**Syed Qutubuddin**, Ph.D. 1983, Carnegie-Mellon University  
*Surfactant and polymer solutions, metal extraction, enhanced oil recovery*

**Robert F. Savinell**, Ph.D. 1977, University of Pittsburgh  
*Applied electrochemistry, electrochemical system simulation and optimization, electrode processes*



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**Faculty**

Amy Ciric	Robert Jenkins
Joel Fried	Yuen-Koh Kao
Stevin Gehrke	Soon-Jai Khang
Rakesh Govind	Jerry Lin
David Greenberg	Glenn Lipscomb
Daniel Hershey	Neville Pinto
Sun-Tak Hwang	Sotiris Pratsinis

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▣ **Process Synthesis**

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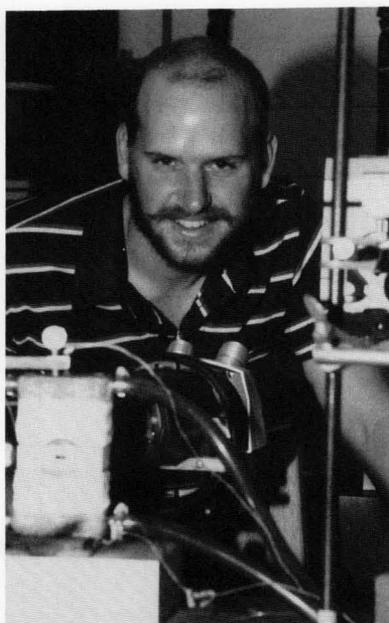


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 Department of Chemical Engineering, # 0171  
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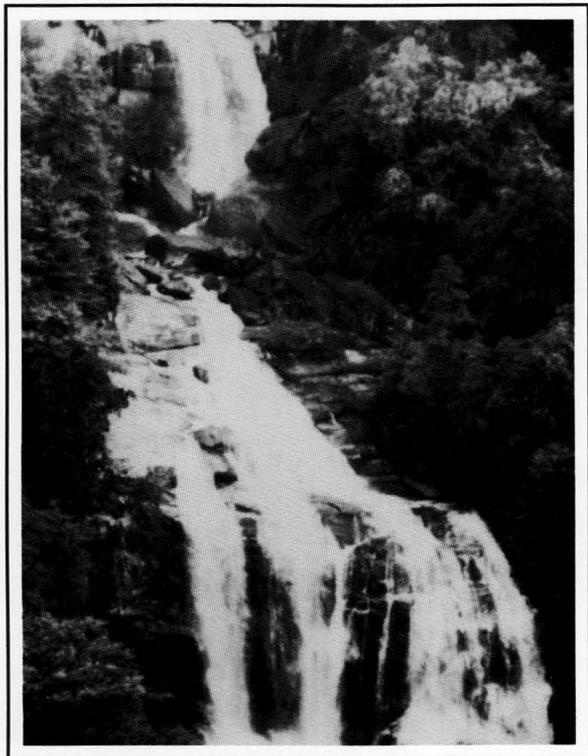
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John N. Beard  
Dan D. Edie  
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## FACULTY

### CHRISTOPHER N. BOWMAN

*Assistant Professor*  
Ph.D., Purdue University, 1991

### DAVID E. CLOUGH

*Professor, Associate Dean for Academic Affairs*  
Ph.D., University of Colorado, 1975

### ROBERT H. DAVIS

*Professor and Acting Chair*  
*Co-Director of Colorado Institute for Research in Biotechnology*  
Ph.D., Stanford University, 1983

### JOHN L. FALCONER

*Professor and Patten Chair*  
Ph.D., Stanford University, 1974

### YURIS O. FUENTES

*Assistant Professor*  
Ph.D., University of Wisconsin-Madison, 1990

### R. IGOR GAMOW

*Associate Professor*  
Ph.D., University of Colorado, 1967

### HOWARD J. M. HANLEY

*Professor Adjoint*  
Ph.D., University of London, 1963

### DHINAKAR S. KOMPALA

*Associate Professor*  
Ph.D., Purdue University, 1984

### WILLIAM B. KRANTZ

*Professor and President's Teaching Scholar,*  
*Co-Director of NSF I/UCRC Center for Separations Using Thin Films*  
Ph.D., University of California, Berkeley, 1968

### RICHARD D. NOBLE

*Professor*  
*Co-Director of NSF I/UCRC Center for Separations Using Thin Films*  
Ph.D., University of California, Davis, 1976

### W. FRED RAMIREZ

*Professor*  
Ph.D., Tulane University, 1965

### ROBERT L. SANI

*Professor*  
*Director of Center for Low-gravity Fluid Mechanics and Transport Phenomena*  
Ph.D., University of Minnesota, 1963

### EDITH M. SEVICK

*Assistant Professor*  
Ph.D., University of Massachusetts, 1989

### KLAUS D. TIMMERHAUS

*Professor and President's Teaching Scholar*  
Ph.D., University of Illinois, 1951

### PAUL W. TODD

*Research Professor*  
Ph.D., University of California, Berkeley, 1964

### RONALD E. WEST

*Professor*  
Ph.D., University of Michigan, 1958



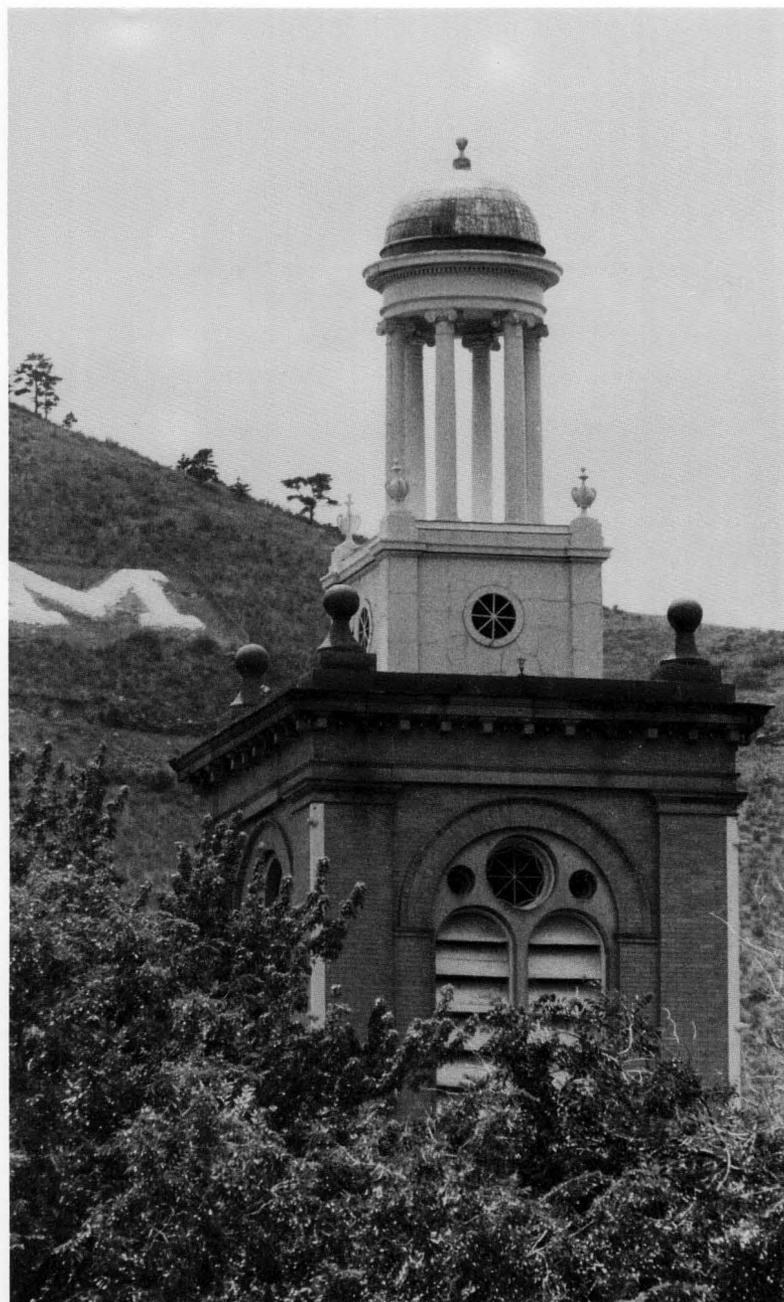
## RESEARCH INTERESTS

- Alternative Energy Sources
- Biotechnology and Bioengineering
- Chemically Specific Separations
- Colloidal Phenomena
- Enhanced Oil Recovery
- Environmental Engineering
- Expert Systems and Fault Detection
- Fluid Dynamics and Suspension Mechanics
- Geophysical Modeling
- Global Change
- Heterogeneous Catalysis
- Interfacial and Surface Phenomena
- Mammalian Cell Culture
- Materials Processing in Low-G
- Mass Transfer
- Membrane Transport and Separations
- Non-Linear Optical Materials
- Numerical and Analytical Modeling
- Polymer Reaction Engineering
- Polymeric Membrane Morphology
- Process Control and Identification
- Semiconductor Processing
- Statistical Mechanics
- Surface Chemistry and Surface Science
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- J. F. ELY**, Professor; Ph.D., Indiana University. *Molecular thermodynamics and transport properties of fluids.*
- J. H. GARY**, Professor Emeritus; Ph.D., University of Florida. *Petroleum refinery processing operations, heavy oil processing, thermal cracking, visbreaking and solvent extraction.*
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- R. L. MILLER**, Associate Professor; Ph.D., Colorado School of Mines. *Liquefaction co-processing of coal and heavy oil, low severity coal liquefaction, particulate removal with venturi scrubbers, interdisciplinary educational methods*
- M. S. SELIM**, Professor; Ph.D., Iowa State University. *Heat and mass transfer with a moving boundary, sedimentation and diffusion of colloidal suspensions, heat effects in gas absorption with chemical reaction, entrance region flow and heat transfer, gas hydrate dissociation modeling.*
- E. D. SLOAN, JR.**, Professor; Ph.D. Clemson University. *Phase equilibrium measurements of natural gas fluids and hydrates, thermal conductivity of coal derived fluids, adsorption equilibria, education methods research.*
- V. F. YESAVAGE**, Professor; Ph.D., University of Michigan. *Vapor liquid equilibrium and enthalpy of polar associating fluids, equations of state for highly non-ideal systems, flow calorimetry.*

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#### ◆◆◆FACULTY RESEARCH AREAS◆◆◆

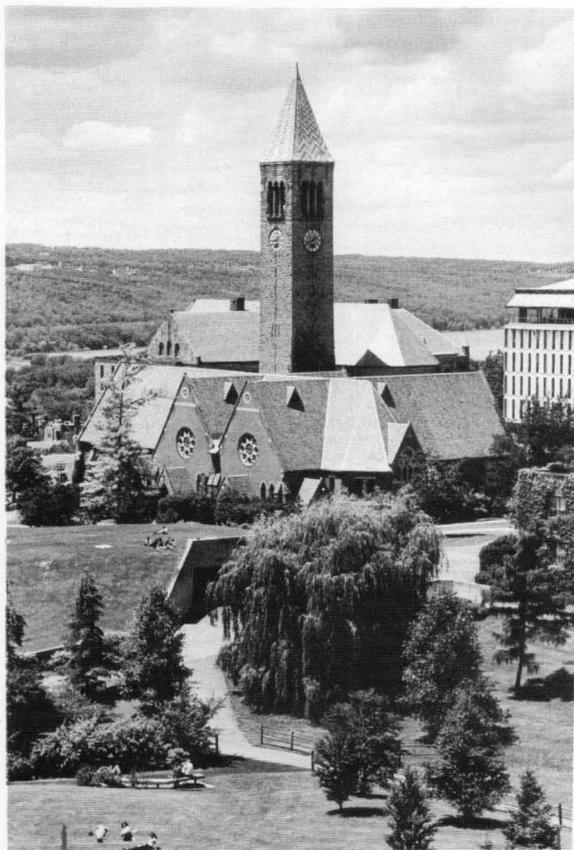
- Luke E. K. Achenie*  
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Modeling of Separation Processes, Fluid-Phase Equilibria
- James P. Bell*  
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Engineering
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Polymer Structure-Property Relationships, Ion-Containing  
And Liquid Crystal Polymers, Polymer Blends

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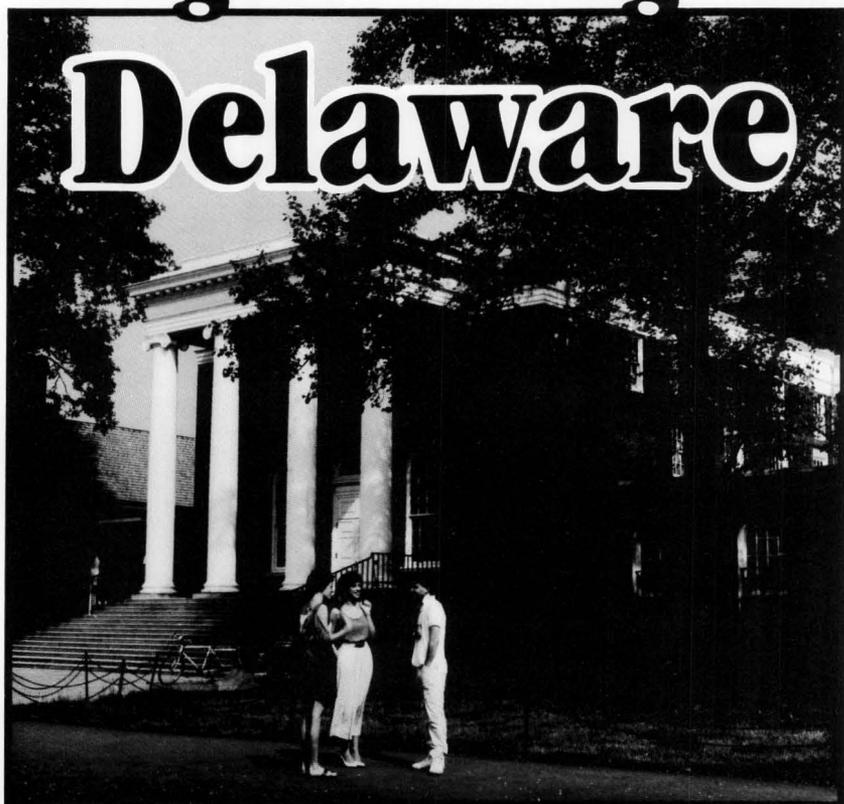
## ***For Further Information, Write:***

Professor William L. Olbricht • Cornell University • Olin Hall of Chemical Engineering • Ithaca, NY 14853-5201

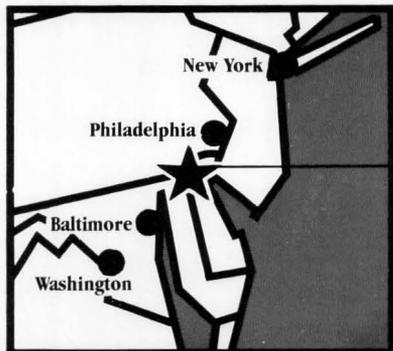
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Mark A. Barteau  
Antony N. Beris  
Kenneth B. Bischoff  
Douglas J. Buttrey  
Costel D. Denson  
Prasad S. Dhurjati  
Henry C. Foley  
Bruce C. Gates  
Eric W. Kaler  
Michael T. Klein  
Abraham M. Lenhoff  
Roy L. McCullough  
Arthur B. Metzner  
Jon H. Olson  
Michael E. Paulaitis  
T.W. Fraser Russell  
Stanley I. Sandler  
Jerold M. Schultz  
Annette D. Shine  
Norman J. Wagner  
Andrew L. Zydney*



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**LEW JOHNS** • Applied Design, Process Control, Energy Systems

**DALE KIRMSE** • Computer Aided Design, Process Control

**HONG H. LEE** • Semiconductor Processing, Reaction Engineering

**GERASIMOS LYBERATOS** • Biochemical Engineering, Chemical Reaction Engineering

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**RANGA NARAYANAN** • Transport Phenomena, Semiconductor Processing

**MARK E. ORAZEM** • Electrochemical Engineering, Semiconductor Processing

**CHANG-WON PARK** • Fluid Mechanics, Polymer Processing

**DINESH O. SHAH** • Surface Sciences, Biomedical Engineering

**SPYROS SVORONOS** • Process Control, Biochemical Engineering

**GERALD WESTERMANN-CLARK** • Electrochemical Engineering, Bioseparations

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University of Florida  
Gainesville, Florida 32611  
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- Chemical Vapor Deposition
- Composite Materials
- Complex Fluids
- Phase Transitions
- Macromolecular Phenomena
- Macromolecular Transport in Polymer Gel Media
- Polymer Processing
- Semiconductor and Superconductor Processing
- Thermodynamics

#### Bioengineering

- Biocatalysis
- Bioseparations
- Bioinformatics

#### Process Synthesis and Control

- Non-Linear Process Control
- Process Optimization
- Expert Systems

#### Surface Science, Catalysis and Inorganic Materials

- Fluid Mechanics of Crystal Growth
- Kinetics and Combustion
- Heterogenous Catalysis and Reactor Design
- Molecular Transport Mechanics in Material Design

#### Other Areas

- Applied and Computational Mathematics
- Air and Water Pollution Control

#### For Information Write to:

Dr. Ravi Chella, Chair  
Graduate Studies  
Department of Chemical Engineering  
FAMU/FSU College of Engineering  
2525 Pottsdammer Street  
Tallahassee, FL 32316-2175  
Ph (904) 487-6170 Fax (904) 487-6150

### Faculty

Pedro Arce Ph.D.  
Purdue University, 1990

Ravi Chella Ph.D.  
University of Massachusetts, 1984

David Edelson Ph.D.  
Yale University, 1949

Hamid Garmestani, Ph.D.\*  
Cornell University, 1989

Peter Gielisse Ph.D.\*  
Ohio State University, 1967

Hwa Lim, Ph.D.\*  
Rochester University, 1986

Bruce Locke Ph.D.  
North Carolina State University, 1989

Srinivas Palanki, Ph.D.  
University of Michigan, 1992

Michael Peters Ph.D.  
Ohio State University, 1981

Sam Riccardi Ph.D.  
Ohio State University, 1949

John Telotte Ph.D.  
University of Florida, 1985

Jorge Viñals Ph.D.\*  
University of Barcelona, Spain, 1981

\*Affiliate Faculty

# Georgia Tech

## CHEMICAL ENGINEERING

### The Faculty and Their Research



Polymer science and engineering

**A.S. Abhiraman**



Heterogeneous catalysis, surface chemistry, reaction kinetics

**Pradeep K. Agrawal**



Process design and control, spouted-bed reactors

**Yaman Arkun**



Microelectronics, polymer processing

**Sue Ann Bidstrup**



Molecular thermodynamics, chemical kinetics, separations

**Charles A. Eckert**



Reactor design, catalysis

**William R. Ernst**



Mechanics of aerosols, buoyant plumes and jets

**Larry J. Forney**



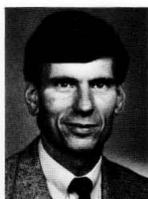
Heat transport phenomena, fluidization

**Charles W. Gorton**



Pulp and paper

**Jeffrey S. Hsieh**



Photochemical processing, mass transfer, chemical vapor deposition

**Paul A. Kohl**



Aerocolloidal systems, interfacial phenomena, fine-particle technology

**Michael J. Matteson**



Polymer engineering, energy conservation, economics

**John D. Muzzy**



Biomechanics, mammalian cell cultures

**Robert M. Nerem**



Emulsion polymerization, latex technology

**Gary W. Poehlein**



Biochemical engineering, mass transfer, reactor design

**Ronnie S. Roberts**



Separation processes, crystallization

**Ronald W. Rousseau**



Biochemical engineering, microbial and animal cell cultures

**Athanassios Sambanis**



Polymer science and engineering

**Robert J. Samuels**



Reactor engineering, process control, polymerization reactor dynamics

**F. Joseph Schork**



Mass transfer, extraction, mixing, non-Newtonian flow

**A. H. Peter Skelland**



Process design and simulation

**Jude T. Sommerfeld**



Process synthesis and simulation, chemical separation, waste management, resource recovery

**D. William Tedder**



Thermodynamic and transport properties, phase equilibria, supercritical gas extraction

**Amyn S. Teja**



Catalysis, kinetics, reactor design

**Mark G. White**



Biochemical engineering, cell-cell interactions, biofluid dynamics

**Timothy M. Wick**



Electrochemical engineering, thermodynamics, air pollution control

**Jack Winnick**



Biofluid dynamics, rheology, transport phenomena

**Ajit P. Yoganathan**

For more information, contact:  
Professor Ronald W. Rousseau, Director  
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Georgia Institute of Technology  
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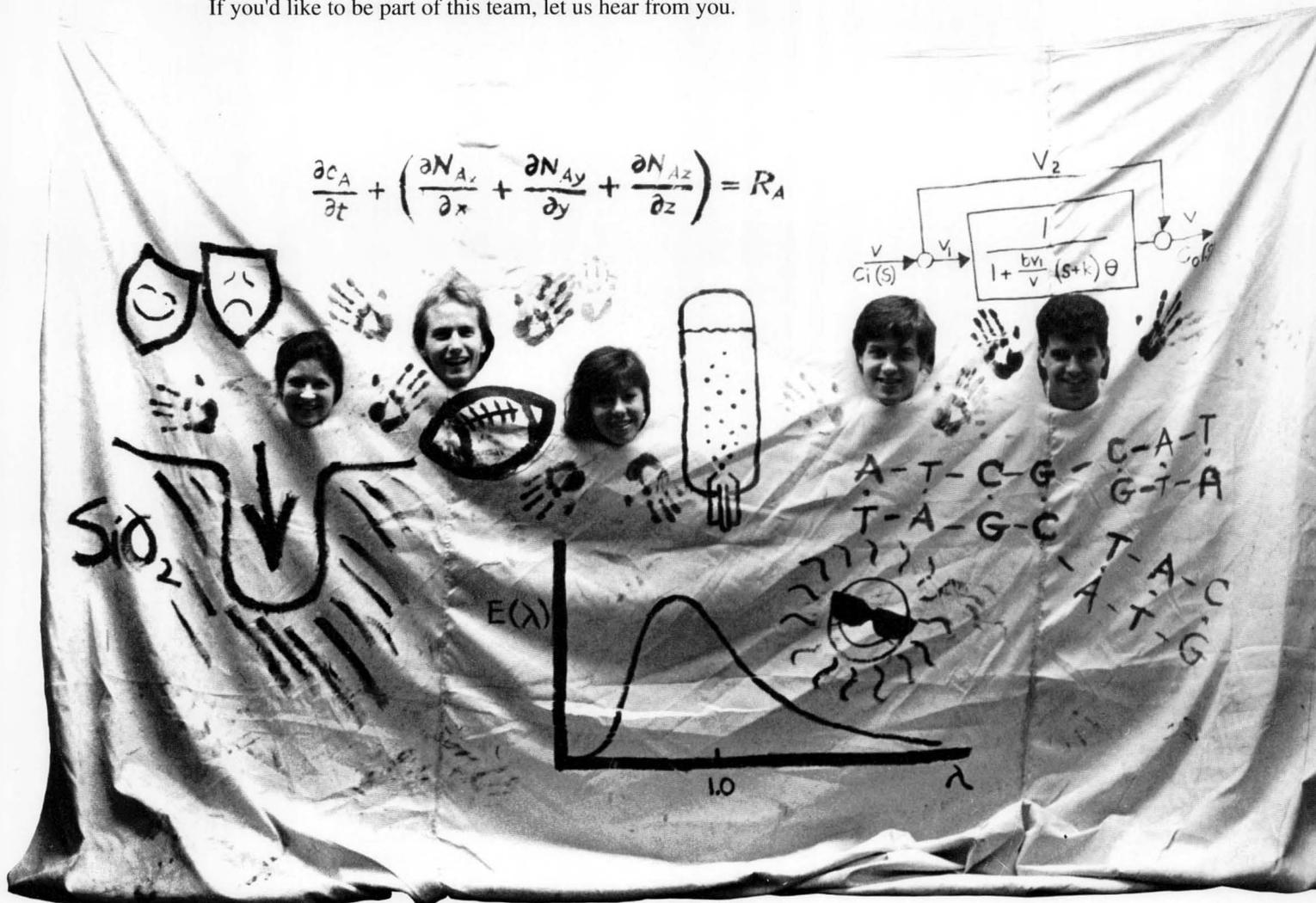
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Applied Transport Phenomena  
Thermodynamics  
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Vemuri Balakotaiah	John Killough	William Prengle	Cynthia Stokes
Abe Dukler	Dan Luss	Raj Rajagopalan	Frank Tiller
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#### **FACULTY**

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Irving F. Miller

Ph.D., University of Michigan, 1960  
Professor and Head

John H. Kiefer

Ph.D., Cornell University, 1961  
Professor

G. Ali Mansoori

Ph.D., University of Oklahoma, 1969  
Professor

Sohail Murad

Ph.D., Cornell University, 1979  
Professor

Ludwig C. Nitsche

Ph.D., Massachusetts Institute of Technology, 1989  
Assistant Professor

John Regalbuto

Ph.D., University of Notre Dame, 1986  
Associate Professor

Satish C. Saxena

Ph.D., Calcutta University, 1956  
Professor

Gina Shreve

Ph.D., University of Michigan, 1991  
Assistant Professor

Stephen Szepe

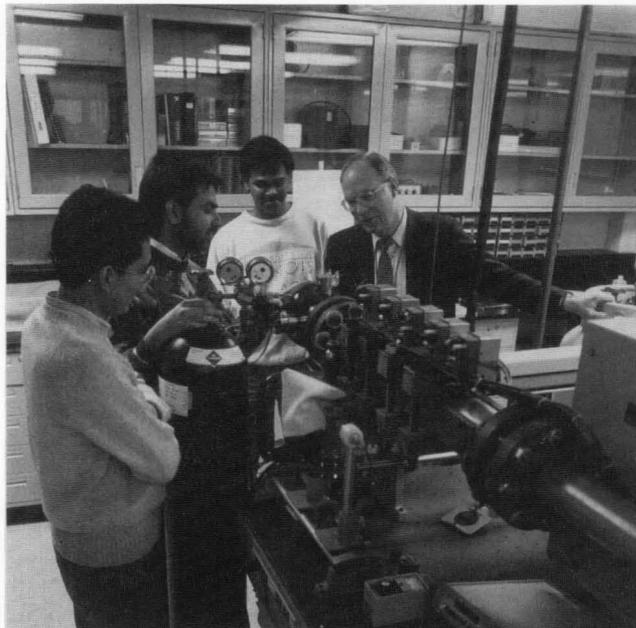
Ph.D., Illinois Institute of Technology, 1966  
Associate Professor

Raffi M. Turian

Ph.D., University of Wisconsin, 1964  
Professor

Bert L. Zuber

Ph.D., Massachusetts Institute of Technology, 1965  
Professor



#### **RESEARCH AREAS**

---

---

**Transport Phenomena:** Slurry transport, multiphase fluid flow and heat transfer, fixed and fluidized bed combustion, indirect coal liquefaction, porous media.

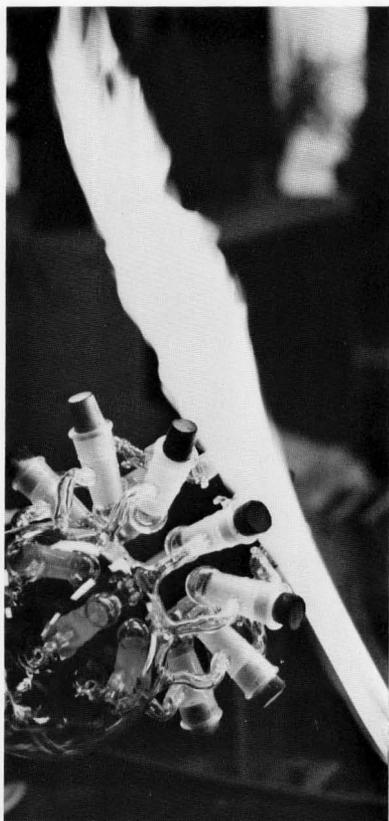
**Thermodynamics:** Transport properties of fluids, statistical mechanics of liquid mixtures, bioseparations, superficial fluid extraction/retrograde condensation, asphaltene characterization.

**Kinetics and Reaction Engineering:** Gas-solid reaction kinetics, diffusion and adsorption phenomena, energy transfer processes, laser diagnostics, combustion chemistry, environmental technology, surface chemistry, optimization, catalyst preparation and characterization, structure sensitivity, supported metals.

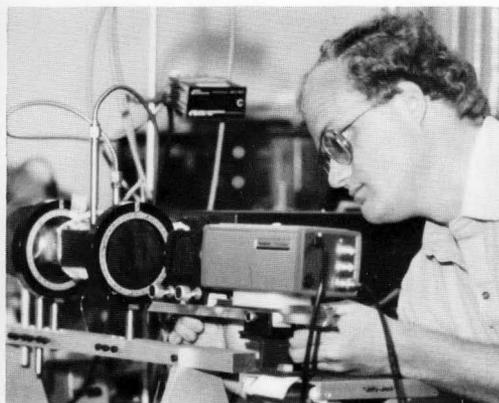
**Bioengineering:** Membrane transport, pulmonary deposition and clearance, biorheology, physiological control systems, bioinstrumentation.

*For more information, write to*

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 Urbana, Illinois 61801

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Transport processes in chemical and biological systems, rheology of polymeric and biological fluids
- *ALI CINAR (Ph.D., Texas A & M)*  
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- *SATISH J. PARULEKAR (Ph.D., Purdue)*  
Biochemical engineering, chemical reaction engineering
- *J. ROBERT SELMAN (Ph.D., California-Berkeley)*  
Electrochemical engineering and electrochemical energy storage
- *FYODOR A. SHUTOV (Ph.D., Institute for Chemical Physics, Moscow)*  
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- *DAVID C. VENERUS (Ph.D., Pennsylvania State U)*  
Polymer rheology and processing, and transport phenomena
- *DARSH T. WASAN (Ph.D., California-Berkeley)*  
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Graduate Admissions Committee  
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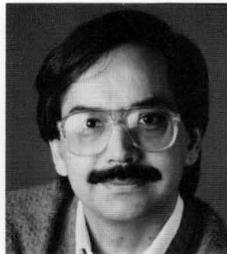
**GREG CARMICHAEL**  
Chair; *U. of Kentucky*,  
1979, Global Change/  
Supercomputing



**J. KEITH BEDDOW**  
*U. of Cambridge*, 1959  
Particle Morphological  
Analysis



**AUDREY BUTLER**  
*U. of Iowa*, 1989  
Chemical Precipita-  
tion Processes



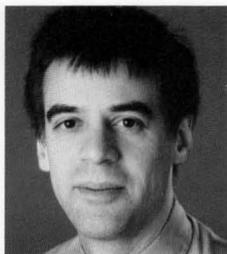
**RAVI DATTA**  
*UCSB*, 1981  
Reaction Engineering/  
Catalyst Design



**JONATHAN DORDICK**  
*MIT*, 1986,  
Biocatalysis and  
Bioprocessing



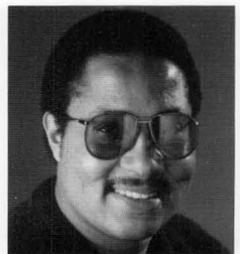
**DAVID LUERKENS**  
*U. of Iowa*, 1980  
Fine Particle Science



**DAVID MURHAMMER**  
*U. of Houston*, 1989  
Animal Cell Culture



**DAVID RETHWISCH**  
*U. of Wisconsin*, 1984  
Membrane Science/  
Catalysis and Cluster  
Science



**V.G.J. RODGERS**  
*Washington U.*, 1989  
Transport Phenomena  
in Bioseparations

For information and application write to:

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Iowa City, Iowa 52242  
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Charles E. Glatz, Ph.D., Wisconsin, 1975.

Peter J. Reilly, Ph.D., Pennsylvania, 1964.

Richard C. Seagrave, Ph.D., Iowa State, 1961.

### ***Catalysis and Reaction Engineering***

L. K. Doraiswamy, Ph.D., Wisconsin, 1952.

Terry S. King, Ph.D., M.I.T., 1979.

Glenn L. Schrader, Ph.D., Wisconsin, 1976.

### ***Energy and Environmental***

George Burnet, Ph.D., Iowa State, 1951.

Thomas D. Wheelock, Ph.D., Iowa State, 1958.

### ***Materials and Crystallization***

Kurt R. Hebert, Ph.D., Illinois, 1985.

Maurice A. Larson, Ph.D., Iowa State, 1958.

Gordon R. Youngquist, Ph.D., Illinois, 1962.

### ***Process Design and Control***

William H. Abraham, Ph.D., Purdue, 1957.

Derrick K. Rollins, Ph.D., Ohio State, 1990.

Dean L. Ulrichson, Ph.D., Iowa State, 1970.

### ***Transport Phenomena and Thermodynamics***

James C. Hill, Ph.D., Washington, 1968.

Kenneth R. Jolls, Ph.D., Illinois, 1966.

**For additional  
information, please write**

Graduate Office

Department of

Chemical Engineering

Iowa State University

Ames, Iowa 50011

or call 515 294-7643

E-Mail N2.TSK@ISUMVS.BITNET

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*Ph.D., University of Texas, Austin*

- Membrane Science
- Sorption and Diffusion in Polymers
- Polymeric Thin Films

## **MICHAEL J. BETENBAUGH**

*Ph.D., University of Delaware*

- Biochemical Kinetics
- Insect Cell Culture
- Recombinant DNA Technology

## **MARC D. DONOHUE**

*Ph.D., University of California, Berkeley*

- Equations of State
- Statistical Thermodynamics
- Phase Equilibria

## **JOSEPH L. KATZ**

*Ph.D., University of Chicago*

- Nucleation
- Crystallization
- Flame Generation of Ceramic Powders

## **MARK A. McHUGH**

*Ph.D., University of Delaware*

- High-Pressure Thermodynamics
- Polymer Solution Thermodynamics
- Supercritical Solvent Extraction

## **W. MARK SALTZMAN**

*Ph.D., Massachusetts Institute of Technology*

- Transport in Biological Systems
- Polymeric Controlled Release
- Cell-Surface Interactions

## **W. H. SCHWARZ**

*Dr. Engr., The Johns Hopkins University*

- Rheology
- Non-Newtonian Fluid Dynamics
- Physical Acoustics and Fluids
- Turbulence

## **KATHLEEN J. STEBE**

*Ph.D., The City University of New York*

- Interfacial Phenomena
- Electropermeability of Biological Membranes
- Surface Effects at Fluid-Droplet Interfaces

# Johns Hopkins

### **For further information contact:**

The Johns Hopkins University  
G.W.C. Whiting School of Engineering  
Department of Chemical Engineering  
34th and Charles Streets  
Baltimore, MD 21218  
(301) 338-7137

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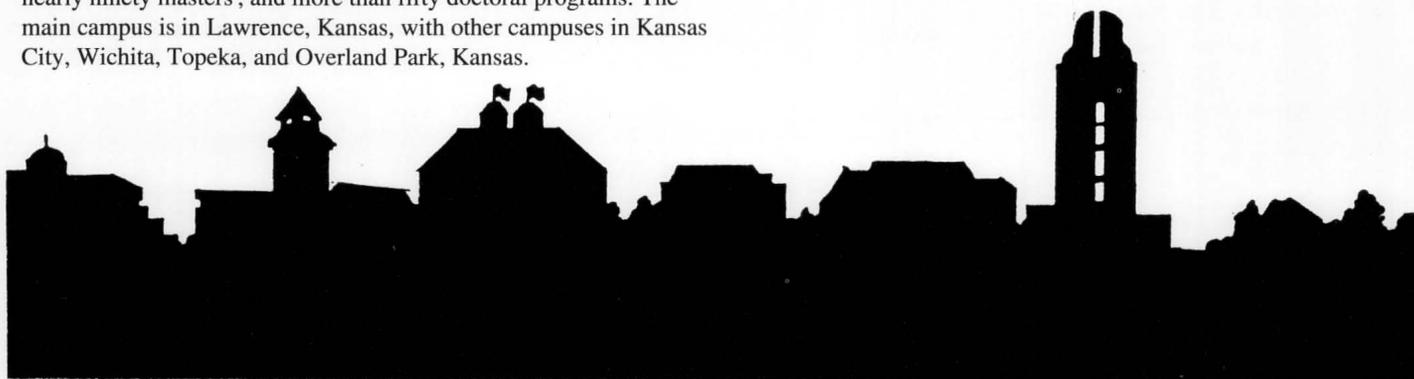
Kenneth A. Bishop (Ph.D., Oklahoma)  
John C. Davis (Ph.D., Wyoming)  
Don W. Green (Ph.D., Oklahoma)  
Colin S. Howat (Ph.D., Kansas)  
Carl E. Locke, Jr., Dean (Ph.D., Texas)  
Russell D. Osterman (Ph.D., Kansas)  
Marylee Z. Southard (Ph.D., Kansas)  
Bala Subramaniam (Ph.D., Notre Dame)  
Galen J. Suppes (Ph.D., Johns Hopkins)  
George W. Swift (Ph.D., Kansas)  
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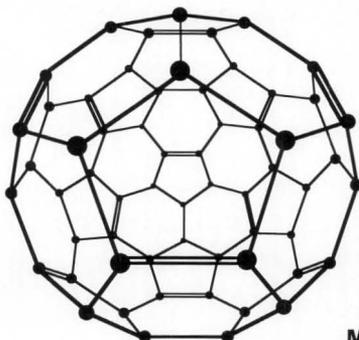
### Areas of Study and Research

Transport Phenomena  
Energy Engineering  
Coal and Biomass Conversion  
Thermodynamics and Phase Equilibrium  
Biochemical Engineering  
Process Dynamics and Control  
Chemical Reaction Engineering  
Materials Science  
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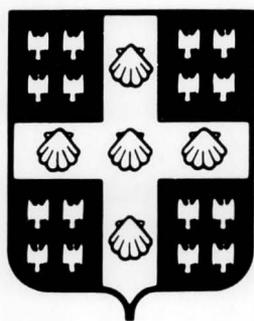
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---

**ABDELLATIF AIT-KADI**  
*Ph.D. École Poly. Montreal  
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**LIONEL CHOPLIN**  
*Ph.D. École Poly. Montreal  
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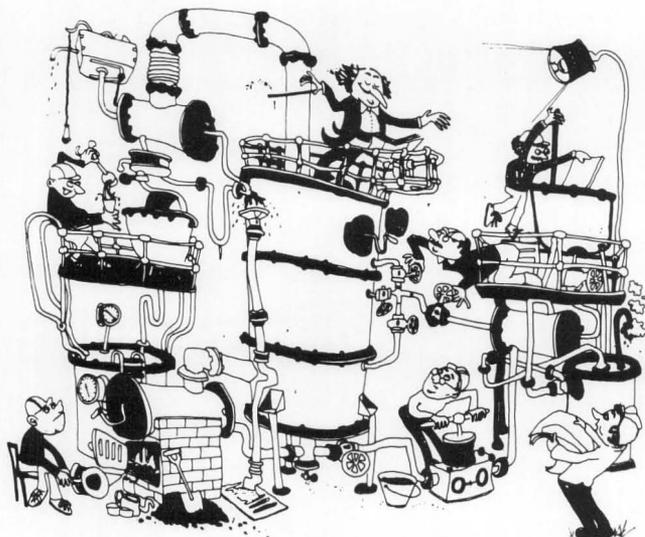
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Dr. Hugo S. Caram  
Chairman, Graduate Admissions Committee  
Department of Chemical Engineering  
Lehigh University  
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- Philip A. Blythe** (University of Manchester)  
fluid mechanics • heat transfer • applied mathematics
- Hugo S. Caram** (University of Minnesota)  
gas-solid and gas-liquid systems • optical techniques • reaction engineering
- Marvin Charles** (Polytechnic Institute of Brooklyn)  
biochemical engineering • bioseparations
- John C. Chen** (University of Michigan)  
two-phase vapor-liquid flow • fluidization • radiative heat transfer • environmental technology
- Mohamed S. El-Aasser** (McGill University)  
polymer colloids and films • emulsion copolymerization • polymer synthesis and characterization
- Christos Georgakis** (University of Minnesota)  
process modeling and control • chemical reaction engineering • batchreactors
- Dennis W. Hess** (Lehigh University)  
microelectronics processing • thin film science and technology
- James T. Hsu** (Northwestern University)  
separation processes • adsorption and catalysis in zeolites
- Arthur E. Humphrey**, Emeritus (Columbia University)  
biochemical processes
- Andrew J. Klein** (North Carolina State University)  
emulsion polymerization • colloidal and surface effects in polymerization
- William L. Luyben** (University of Delaware)  
process design and control • distillation
- Janice A. Phillips** (University of Pennsylvania)  
biochemical engineering • instrumentation/control of bioreactors • mammalian cell culture
- Maria M. Santore** (Princeton University)  
polymers adsorption processes and blend stability
- William E. Schiesser** (Princeton University)  
numerical algorithms and software in chemical engineering
- Cesar A. Silebi** (Lehigh University)  
separation of colloidal particles • electrophoresis • mass transfer
- Leslie H. Sperling** (Duke University)  
mechanical and morphological properties of polymers • interpenetrating polymer networks
- Fred P. Stein** (University of Michigan)  
thermodynamic properties of mixtures
- Harvey G. Stenger, Jr.** (Massachusetts Institute of Technology)  
reactor engineering
- Israel E. Wachs** (Stanford University)  
materials synthesis and characterization • surface chemistry • heterogeneous catalysis
- Leonard A. Wenzel**, Emeritus (University of Michigan)  
thermodynamics

# LOUISIANA STATE UNIVERSITY

## CHEMICAL ENGINEERING GRADUATE SCHOOL



### THE CITY

Baton Rouge is the state capital and home of the major state institution for higher education — LSU. Situated in the Acadian region, Baton Rouge blends the Old South and Cajun Cultures. The Port of Baton Rouge is a main chemical shipping point, and the city's economy rests heavily on the chemical and agricultural industries. The great outdoors provide excellent recreational activities year-round. The proximity of New Orleans provides for superb nightlife, especially during Mardi Gras.

### THE DEPARTMENT

- M.S. and Ph.D. Programs
- Approximately 70 Graduate Students

#### DEPARTMENTAL FACILITIES

- IBM 4341 and 9370 with more than 70 color graphics terminals and PC's
- Analytical Facilities including GC/MS, FTIR, FT-NMR, LC, GC, AA, XRD, . . .
- Vacuum to High Pressure Facilities for kinetics, catalysis, thermodynamics, supercritical processing
- Shock Tube and Combustion Laboratories
- Laser Doppler Velocimeter Facility
- Bench Scale Fermentation Facilities
- Polymer Processing Equipment

### TO APPLY, CONTACT

DIRECTOR OF GRADUATE INSTRUCTION  
Department of Chemical Engineering  
Louisiana State University  
Baton Rouge, LA 70803

### FACULTY

- J.R. COLLIER** (Ph.D., Case Institute)  
*Polymers, Textiles, Fluid Flow*
- A.B. CORRIPIO** (Ph.D., Louisiana State University)  
*Control, Simulation, Computer-Aided Design*
- K.M. DOOLEY** (Ph.D., University of Delaware)  
*Heterogeneous Catalysis, Reaction Engineering*
- G.L. GRIFFIN** (Ph.D., Princeton University)  
*Heterogeneous Catalysis, Surfaces, Materials Processing*
- F.R. GROVES** (Ph.D., University of Wisconsin)  
*Control, Modeling, Separation Processes*
- D.P. HARRISON** (Ph.D., University of Texas)  
*Fluid-Solid Reactions, Hazardous Wastes*
- M. HJORTSØ** (Ph.D., University of Houston)  
*Biotechnology, Applied Mathematics*
- F.C. KNOPF** (Ph.D., Purdue University)  
*Computer-Aided Design, Supercritical Processing*
- E. McLAUGHLIN** (D.Sc., University of London)  
*Thermodynamics, High Pressures, Physical Properties*
- R.W. PIKE** (Ph.D., Georgia Institute of Technology)  
*Fluid Dynamics, Reaction Engineering, Optimization*
- G.L. PRICE** (Ph.D., Rice University)  
*Heterogeneous Catalysis, Surfaces*
- D.D. REIBLE** (Ph.D., California Institute of Technology)  
*Environmental Chemodynamics, Transport Modeling*
- R.G. RICE** (Ph.D., University of Pennsylvania)  
*Mass Transfer, Separation Processes*
- A.M. STERLING** (Ph.D., University of Washington)  
*Transport Phenomena, Combustion*
- L.J. THIBODEAUX** (Ph.D., Louisiana State University)  
*Chemodynamics, Hazardous Waste*
- R.D. WESSON** (Ph.D., University of Michigan)  
*Semi-Crystalline Polymer Processing*
- D.M. WETZEL** (Ph.D., University of Delaware)  
*Physical Properties, Hazardous Wastes*

### FINANCIAL AID

- Assistantships at \$14,400 (waiver of out-of-state tuition)
- Dean's Fellowships at \$17,000 per year plus tuition and a travel grant
- Special industrial and alumni fellowships for outstanding students
- Some part-time teaching experience available for graduate students interested in an academic career

# University of Maine



## • Faculty and Research Interests •

**DOUGLAS BOUSFIELD** Ph.D. (U.C. Berkeley)  
Fluid Mechanics, Rheology, Coating Processes,  
Particle Motion Modeling

**WILLIAM H. CECKLER** Sc.D. (M.I.T.)  
Heat Transfer, Pressing & Drying Operations,  
Energy from Low BTU Fuels, Process Simulation  
& Modeling

**ALBERT CO** Ph.D. (Wisconsin)  
Polymeric Fluid Dynamics, Rheology, Transport  
Phenomena, Numerical Methods

**JOSEPH M. GENCO** Ph.D. (Ohio State)  
Process Engineering, Pulp and Paper Technology,  
Wood Delignification

**JOHN C. HASSLER** Ph.D. (Kansas State)  
Process Control, Numerical Methods,  
Instrumentation and Real Time Computer  
Applications

**MARQUITA K HILL** Ph.D. (U.C. Davis)  
Environmental Science, Waste Management  
Technology

**JOHN J. HWALEK** Ph.D. (Illinois)  
Liquid Metal Natural Convection, Electronics  
Cooling, Process Control Systems

**ERDOGAN KIRAN** Ph.D. (Princeton)  
Polymer Physics & Chemistry, Supercritical  
Fluids, Thermal Analysis & Pyrolysis, Pulp &  
Paper Science

**DAVID J. KRASKE** (Chairman)  
Ph.D. (Inst. Paper Chemistry)  
Pulp, Paper & Coating Technology, Additive  
Chemistry, Cellulose & Wood Chemistry

**PIERRE LEPOUTRE** Ph.D. (North Carolina  
State University)  
Surface Physics and Chemistry, Materials  
Science, Adhesion Phenomena

**KENNETH I. MUMME** Ph.D. (Maine)  
Process Simulation and Control, System  
Identification & Optimization

**HEMANT PENDSE** Ph.D. (Syracuse)  
Colloidal Phenomena, Particulate & Multiphase  
Processes, Porous Media Modeling

**EDWARD V. THOMPSON** Ph.D., (Polytechnic  
Institute of Brooklyn)  
Thermal & Mechanical Properties of Polymers,  
Papermaking and Fiber Physics, Recycle Paper

## Programs and • Financial Support •

Eighteen research groups attack fundamental problems leading to M.S. and Ph.D. degrees. Industrial fellowships, university fellowships, research assistantships and teaching assistantships are available. Presidential fellowships provide \$4,000 per year in addition to the regular stipend and free tuition.

## • The University •

The spacious campus is situated on 1,200 acres overlooking the Penobscot and Stillwater Rivers. Present enrollment of 12,000 offers the diversity of a large school, while preserving close personal contact between peers and faculty. The University's Maine Center for the Arts, the Hauck Auditorium, and Pavilion Theatre provide many cultural opportunities, in addition to those in the nearby city of Bangor. Less than an hour away from campus are the beautiful Maine Coast and Acadia National park, alpine and cross-country ski resorts, and northern wilderness areas of Baxter State Park and Mount Katahdin.

Enjoy life, work hard and earn your graduate degree in one of the most beautiful spots in the world.

## Call Collect or Write

Doug Bousfield  
Department of Chemical Engineering  
Jeness Hall, Box B • University of Maine  
Orono, Maine 04469-0135  
(207) 581-2300

# UMBC

UNIVERSITY OF MARYLAND  
BALTIMORE COUNTY

## GRADUATE STUDY IN BIOCHEMICAL ENGINEERING

FOR ENGINEERING AND SCIENCE MAJORS

### Emphasis

The UMBC Chemical and Biochemical Engineering Program offers graduate programs leading to M.S. and Ph.D. degrees in Chemical Engineering with a primary research focus in biochemical engineering.

### Facilities

The 6000 square feet of space dedicated to faculty and graduate student research includes state-of-the-art laboratory facilities. The BioProcess Scale-Up Facility on the College Park Campus is also available for use with classical microbial systems. A new Engineering and Computer Science building with an additional 7,000 square feet of laboratory space for Chemical and Biochemical Engineering will open in the fall of 1992.

### Faculty

**D.F. Bruley, Ph.D.** Tennessee

*Biodownstream processing and transport processes in the microcirculation; Process simulation and control.*

**T. W. Cadman, Ph.D.** Carnegie Mellon  
*Bioprocess modeling, control, and optimization; Educational software development*

**A. Gomezplata, Ph.D.** Rensselaer  
*Heterogeneous flow systems; Simultaneous mass transfer and chemical reactions*

**C. S. Lee, Ph.D.** Rensselaer  
*Bioseparations; Biosensors; Protein adsorption at interfaces*

**J. A. Lumpkin, Ph.D.** Pennsylvania  
*Analytical chemi- and bioluminescence; Kinetics of enzymatic reactions; Protein oxidation*

**A. R. Moreira, Ph.D.\*** Pennsylvania  
*rDNA fermentation; Regulatory issues; Scale-up; Downstream processing*

**G. F. Payne, Ph.D.\*** Michigan  
*Plant cell tissue culture; Streptomyces bioprocessing; Adsorptive separations; Toxic waste treatment*

**G. Rao, Ph.D.\*** Drexel  
*Animal cell culture; Oxygen toxicity; Biosensing*

**J. Rosenblatt, Ph.D.** Berkeley  
*Biomedical engineering; Drug delivery; Collagen applications*

**M. R. Sierks, Ph.D.** Iowa State  
*Protein engineering; Site-directed mutagenesis; Catalytic antibodies*

**D. I. C. Wang, Ph.D.\*\*** Pennsylvania  
*Bioreactors; Bioinstrumentation; Protein refolding*

\* Joint appointment with the Maryland Biotechnology Institute  
\*\* Adjunct professor/Eminent scholar

## GRADUATE STUDY IN BIOCHEMICAL ENGINEERING

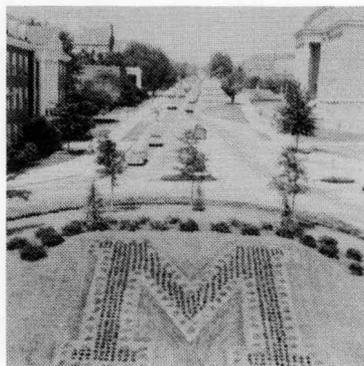
FOR ENGINEERING AND SCIENCE MAJORS

### For further information contact:

Dr. A. R. Moreira  
Department of Chemical and Biochemical  
Engineering  
University of Maryland Baltimore County  
Baltimore, Maryland 21288  
(301) 455-3400

# University of Maryland

## College Park

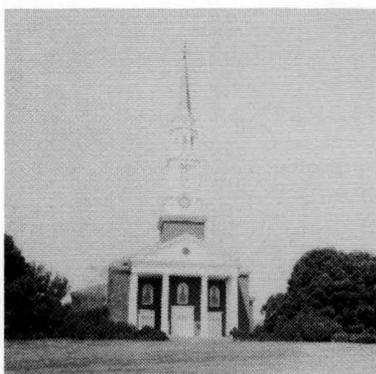
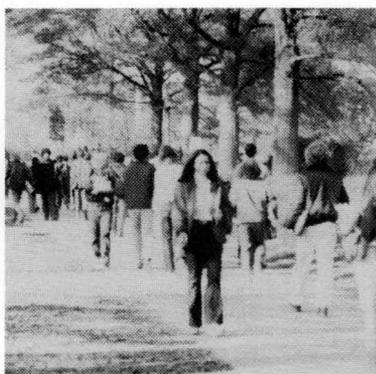


### Location:

*The University of Maryland College Park is located approximately ten 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 brings one to the historic Chesapeake Bay.*

### Faculty:

William E. Bentley  
Richard V. Calabrese  
Kyu Yong Choi  
Larry L. Gasner  
James W. Gentry  
Michael L. Mavrovouniotis  
Thomas J. McAvoy  
Thomas M. Regan  
Theodore G. Smith  
Nam Sun Wang  
William A. Weigand  
Evangelhos Zafiriou



### Degrees Offered:

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

### Financial Aid Available:

Teaching and Research Assistantships at \$12,880/yr., plus tuition



### Research Areas:

Aerosol Science  
Artificial Intelligence  
Biochemical Engineering  
Fermentation  
Neural Computation  
Polymer Processing  
Polymer Reaction Engineering  
Process Control  
Recombinant DNA Technology  
Separation Processes  
Systems Engineering  
Turbulence and Mixing

### For Applications and Further Information, Write:

Chemical Engineering Graduate Studies  
Department of Chemical Engineering  
University of Maryland  
College Park, MD 20742-2111

# University of Massachusetts at Amherst

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

### Faculty

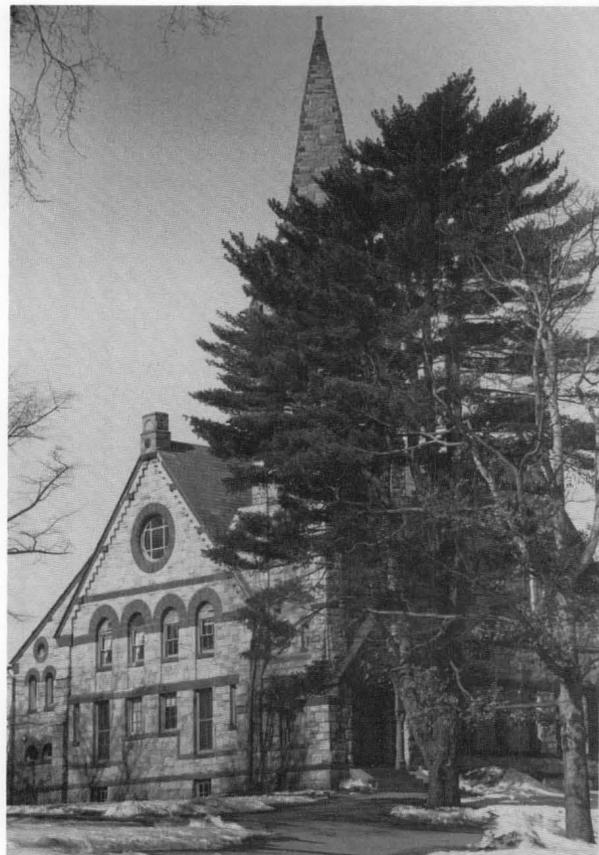
M. F. Doherty, Ph.D. (Cambridge), Head  
W. C. Conner, Ph.D. (Johns Hopkins)  
M. R. Cook, Ph.D. (Harvard)  
J. M. Douglas, Ph.D. (Delaware)  
V. Haensel, Ph.D. (Northwestern)  
M. P. Harold, Ph.D. (Houston)  
R. L. Laurence, Ph.D. (Northwestern)  
M. F. Malone, Ph.D. (Massachusetts)  
P. A. Monson, Ph.D. (London)  
K. M. Ng, Ph.D. (Houston)  
J. W. van Egmond (Stanford)  
P. R. Westmoreland, Ph.D. (M.I.T.)  
H. H. Winter, Ph.D. (Stuttgart)

### Current Areas of Research

- Combustion, Plasma Processing
- Process Synthesis, Design of Polymer and Solids Processes
- Statistical Thermodynamics, Phase Behavior
- Control System Synthesis
- Fluid Mechanics, Rheology
- Polymer Processing, Composites
- Catalysis and Kinetics, Reaction Dynamics
- Design of Multiphase and Polymerization Reactors
- Nonideal Distillation, Adsorption, Crystallization
- Computer Aided Design, Optimization
- Computational Chemistry

### Design and Control Center

The Department has a research center in design and control, which is sponsored by industrial companies.



### Financial Support

All students are awarded full financial aid at a nationally competitive rate.

### Location

The Amherst Campus of the University is in a small New England town in Western Massachusetts. Set amid farmland and rolling hills, the area offers pleasant living conditions and extensive recreational facilities.

*For application forms and further information on fellowships and assistantships, academic and research programs, and student housing, write:*

GRADUATE PROGRAM DIRECTOR  
DEPARTMENT OF CHEMICAL ENGINEERING  
159 GOESSMANN LABORATORY  
UNIVERSITY OF MASSACHUSETTS  
AMHERST, MA 01003

The University of Massachusetts at Amherst prohibits discrimination on the basis of race, color, religion, creed, sex, sexual orientation, age, marital status, national origin, disability or handicap, political belief or affiliation, membership or non-membership in any organization, or veteran status, in any aspect of the admission or treatment of students or in employment.

# CHEMICAL ENGINEERING AT



# MIT

*MIT is located in Cambridge, just across the Charles River from Boston, a few minutes by subway from downtown Boston on the one hand and Harvard Square on the other. The heavy concentration of colleges, hospitals, research facilities, and high technology industry provides a populace that demands and finds an unending variety of theaters, concerts, restaurants, museums, bookstores, sporting events, libraries, and recreational facilities.*

With the largest chemical engineering research faculty in the country, the Department of Chemical Engineering at MIT offers programs of research and teaching which span the breadth of chemical engineering with unprecedented depth in fundamentals and applications. The Department offers three levels of graduate programs, leading to Master's, Engineer's, and Doctor's degrees. In addition, graduate students may earn a Master's degree through the **David H. Koch School of Chemical Engineering Practice**, a unique internship program that stresses defining and solving industrial problems by applying chemical engineering fundamentals. Students in this program spend half a semester at each of two Practice School Stations, including Dow Chemical in Midland, Michigan, and Merck Pharmaceutical Manufacturing Division in West Point, Pennsylvania, in addition to one or two semesters at MIT.

## RESEARCH AREAS

**Artificial Intelligence • Biomedical Engineering**  
**Biotechnology**  
**Catalysis and Reaction Engineering**  
**Combustion • Computer-Aided Design**  
**Electrochemistry • Energy Conversion**  
**Environmental Engineering • Fluid Mechanics**  
**Kinetics and Reaction Engineering**  
**Microelectronic Materials Processing**  
**Polymers • Process Dynamics and Control**  
**Surfaces and Colloids • Transport Phenomena**

## FOR MORE INFORMATION CONTACT

Chemical Engineering Graduate Office, 66-366  
Massachusetts Institute of Technology, Cambridge, MA 02139-4307  
Phone: (617) 253-4579; FAX: (617) 253-9695

## FACULTY

**R.A. Brown, Department Head**

**R.C. Armstrong**

**P.I. Barton**

**J.M. Beér**

**E.D. Blankschtein**

**H. Brenner**

**L.G. Cima**

**R.E. Cohen**

**C.K. Colton**

**C.L. Cooney**

**W.M. Deen**

**K.K. Gleason**

**J.G. Harris**

**T.A. Hatton**

**J.B. Howard**

**K.F. Jensen**

**R.S. Langer**

**G.J. McRae**

**E.W. Merrill**

**C.M. Mohr**

**G.C. Rutledge**

**A.F. Sarofim**

**H.H. Sawin**

**K.A. Smith**

**Ge. Stephanopoulos**

**Gr. Stephanopoulos**

**M.F. Stephanopoulos**

**J.W. Tester**

**P.S. Virk**

**D.I.C. Wang**

**J.Y. Ying**

# Chemical Engineering at

# The University of Michigan

## Faculty

1. **Johannes Schwank** Chair, Heterogeneous catalysis, surface science
2. **Stacy G. Bike** Colloids, transport, electrokinetic phenomena
3. **Dale E. Briggs** Coal processes
4. **Mark A. Burns** Biochemical and field-enhanced separations
5. **Brice Carnahan** Numerical methods, process simulation
6. **Rane L. Curl** Rate processes, mathematical modeling
7. **Frank M. Donahue** Electrochemical engineering
8. **H. Scott Fogler** Flow in porous media, microelectronics processing
9. **John L. Gland** Surface science
10. **Erdogan Gulari** Interfacial phenomena, catalysis, surface science
11. **Robert H. Kadlec** Ecosystems, process dynamics
12. **Costas Kravaris** Nonlinear process control, system identification
13. **Jennifer J. Linderman** Engineering approaches to cell biology
14. **Bernhard O. Palsson** Cellular bioengineering
15. **Phillip E. Savage** Reaction pathways in complex systems
16. **Levi T. Thompson, Jr.** Catalysis, processing materials in space
17. **Henry Y. Wang** Biotechnology processes, industrial biology
18. **James O. Wilkes** Numerical methods, polymer processing
19. **Robert M. Ziff** Aggregation processes, statistical mechanics



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### For More Information, Contact:

Graduate Program Office, Department of Chemical Engineering / The University of Michigan / Ann Arbor, MI 48109-2136 / 313 763-1148

# GRADUATE STUDY IN CHEMICAL ENGINEERING AT MICHIGAN STATE UNIVERSITY



The Department of Chemical Engineering offers Graduate Programs leading to M.S. and Ph.D. degrees in Chemical Engineering. The faculty conduct fundamental and applied research in a variety of Chemical Engineering disciplines. The Michigan Biotechnology Institute, the Composite Materials and Structures Center, and the Crop Bioprocessing Center provide a forum for interdisciplinary work in current high technology areas.

**ASSISTANTSHIPS** • Half-time graduate assistantships for incoming Master's candidates are expected to pay \$13,500 per year net after all tuition and fees; the corresponding stipend for Ph.D. students is about \$14,300.

Theses may be written on the subject covered by the research assistantship.

**FELLOWSHIPS** • Available appointments pay up to \$18,000 per year, plus all tuition and fees.

## • FACULTY AND RESEARCH INTERESTS •

**D. K. ANDERSON**, Chairperson

*Ph.D., 1960, University of Washington*

Transport Phenomena, Diffusion in Polymer Solutions

**K. A. BERGLUND**

*Ph.D., 1981, Iowa State University*

Sensors, Applied Spectroscopy, Food and Biochemical Engineering, Inorganic Polymers.

**D. M. BRIEDIS**

*Ph.D., 1981, Iowa State University*

Surface Phenomena in Crystallization Processes, Biochemical Engineering, Ceramic Powder Processing

**C. M. COOPER**, Professor Emeritus

*Sc.D., 1949, Massachusetts Institute of Technology*

Thermodynamics and Phase Equilibria, Modeling of Transport Processes

**L. T. DRZAL**

*Ph.D., 1974, Case Western Reserve University*

Surface and Interfacial Phenomena, Adhesion, Composite Materials, Surface Characterization, Surface Modification of Polymers, Composite Processing

**H. E. GRETHLEIN**

*Ph.D., 1962, Princeton University*

Biomass Conversion, Bio-Degradation, Waste Treatment, Bioprocess Development, Distillation, Biochemical Engineering

**E. A. GRULKE**

*Ph.D., 1975, Ohio State University*

Mass Transport Phenomena, Polymer Devolatilization, Biochemical Engineering, Food Engineering

**M. C. HAWLEY**

*Ph.D., 1964, Michigan State University*

Kinetics, Catalysis, Reactions in Plasmas, Polymerization Reactions, Composite Processing, Biomass Conversion, Reaction Engineering

**K. JAYARAMAN**

*Ph.D., 1975, Princeton University*

Polymer Rheology, Processing of Polymer Blends and Composites, Computational Methods

**C. T. LIRA**

*Ph.D., 1986, University of Illinois at Urbana-Champaign*

Thermodynamics and Phase Equilibria of Complex Systems, Supercritical Fluid Studies

**D. J. MILLER**

*Ph.D., 1982, University of Florida*

Kinetics and Catalysis, Reaction Engineering, Coal Gasification, Catalytic Conversion of Biomass-Based Materials

**R. NARAYAN**

*Ph.D., 1976, University of Bombay*

Engineering and Design of Natural-Synthetic Polymer Composite Systems, Polymer Blends and Alloys, Biodegradable Plastics, Low-Cost Composites Using Recycled/Reclaimed and Natural Polymers

**C. A. PETTY**

*Ph.D., 1970, University of Florida*

Fluid Mechanics, Turbulent Transport Phenomena, Solid-Fluid and Liquid-Liquid Separations, Polymer Composite Processing

**A. B. SCRANTON**

*Ph.D., 1990, Purdue University*

Polymer Science and Engineering, Polymer Complexation and Network Formation, Applications of NMR Spectroscopy, Molecular Modeling

**B. W. WILKINSON**, Professor Emeritus

*Ph.D., 1958, Ohio State University*

Energy Systems and Environmental Control, Nuclear Reactor, Radioisotope Applications

**R. M. WORDEN**

*Ph.D., 1986, University of Tennessee*

Biochemical Engineering, Immobilized Cell Technology, Food Engineering

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### FOR ADDITIONAL INFORMATION WRITE

Chairperson • Department of Chemical Engineering • A202 Engineering Building  
Michigan State University • East Lansing, Michigan 48824-1226

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# CHEMICAL ENGINEERING

## Michigan Technological University

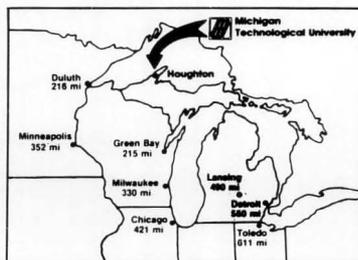


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Combine a first-rate chemical engineering education with the environmentally exciting surroundings of the Keweenaw Peninsula.

**Michigan Tech.** Established in 1885. One of four nationally-recognized research institutions in the state of Michigan. 6,500 undergraduate students. 500 graduate students.

**Michigan Tech.** The 9th largest chemical engineering program in the country, with a vital and focussed graduate program.



### CONTACT

Department of Chemical Engineering  
Michigan Technological University  
1400 Townsend Drive  
Houghton, MI 49931-1295  
906/487-2047  
FAX 906/487-2061

## Chemical Engineering Faculty

### Process and plant design

Bruce A. Barna, Associate Professor  
Ph.D., New Mexico State, 1985

### Polymerization, polymer materials, nonlinear dynamics

Gerard T. Caneba, Assistant Professor  
Ph.D., University of California Berkeley, 1985

### Process control, neural networks

Tomas B. Co, Assistant Professor  
Ph.D., Massachusetts, 1988

### Energy transfer and excited state processes

Edward R. Fisher, Professor and Head  
Ph.D., Johns Hopkins University, 1965

### Numerical analysis, absorption, process safety

Anton J. Pintar, Associate Professor  
Ph.D., Illinois Institute of Technology, 1968

### Transport processes and process scaleup

Davis W. Hubbard, Professor  
Ph.D., University of Wisconsin Madison, 1964

### Process control, energy systems

Nam K. Kim, Associate Professor  
Ph.D., Montana State, 1982

### Polymer rheology, liquid crystals, composites

Faith A. Morrison, Assistant Professor  
Ph.D., Massachusetts, 1988

### Surface science, sol-gel processing

Michael E. Mullins, Associate Professor  
Ph.D., Rochester, 1983

### Polymer Science, polymer and composite processing

John G. Williams, Professor  
Ph.D., Melbourne University

Michigan Technological University is an equal opportunity educational institution/equal opportunity employer.



Department of Chemical Engineering



M.S. and Ph.D. Degrees

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## **FACULTY AND RESEARCH INTERESTS**

---

**N. L. BOOK (Ph.D., Colorado)**

- Computer Aided Process Design • Bioconversion

**O. K. CROSSER (Ph.D., Rice)**

- Transport Properties • Kinetics • Catalysis

**D. FORCINITI (Ph.D., North Carolina State)**

- Bioseparations • Thermodynamics
- Statistical Mechanics

**J. W. JOHNSON (Ph.D. Missouri)**

- Electrode Reactions • Adsorption

**A. I. LIAPIS (Ph.D., ETH-Zurich)**

- Adsorption • Affinity Chromatography • Perfusion Chromatography • Transport Phenomena
- Lyophilization (Freeze Drying)

**D. B. MANLEY (Ph.D., Kansas)**

- Thermodynamics • Vapor-Liquid Equilibrium

**N. C. MOROSOFF (Ph.D., Brooklyn Polytech)**

- Plasma Polymerization • Membranes

**P. NEOGI (Ph.D., Carnegie-Mellon)**

- Interfacial and Transport Phenomena

**G. K. PATTERSON (Ph.D., Missouri-Rolla)**

- Mixing • Polymer Rheology

**X B REED, JR. (Ph.D., Minnesota)**

- Fluid Mechanics • Drop and Particle Mechanics
- Transport Phenomena • Turbulence Structure
- Turbulence Modeling, including Reactions

**S. L. ROSEN (Ph.D., Cornell)**

- Polymerization Reactions • Applied Rheology
- Polymeric Materials

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

- Bioengineering

**R. C. WAGGONER (Ph.D., Texas A&M)**

- Multistage Mass Transfer Operations • Distillation
- Extraction • Process Control

**R. M. YBARRA (Ph.D., Purdue)**

- Rheology of Polymer Solutions • Chemical Reaction Kinetics



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

**Contact Dr. X B Reed, Graduate Coordinator  
Chemical Engineering Department  
University of Missouri - Rolla  
Rolla, Missouri 65401  
Telephone (314) 341-4416**

# GRADUATE STUDIES

# NJIT

CHEMICAL ENGINEERING

The Department of Chemical Engineering, Chemistry and Environmental Science offers excellent opportunities for interdisciplinary research and graduate studies, particularly in the areas of hazardous waste treatment, materials science, and biotechnology.

Both master's and doctoral degrees are offered in a growing program that has national and international research ties.

## RESOURCES

□ 20,000 square feet of modern laboratory and computing facilities □ Internationally respected faculty □ Major research facilities in hazardous substance management and microelectronics fabrication

## SUPPORT

□ Nearly \$2 million in annual research support from state, federal and industrial sponsors □ Graduate Cooperative Education □ Financial assistance programs

## FLEXIBILITY

□ Part-time or full-time □ Evening study □ Interdisciplinary research □ Diverse areas of specialization □ M.S. and Ph.D. degrees



For program information, contact:  
Dr. Dana Knox, Graduate Advisor  
Department of Chemical Engineering,  
Chemistry and Environmental Science  
201-596-3599

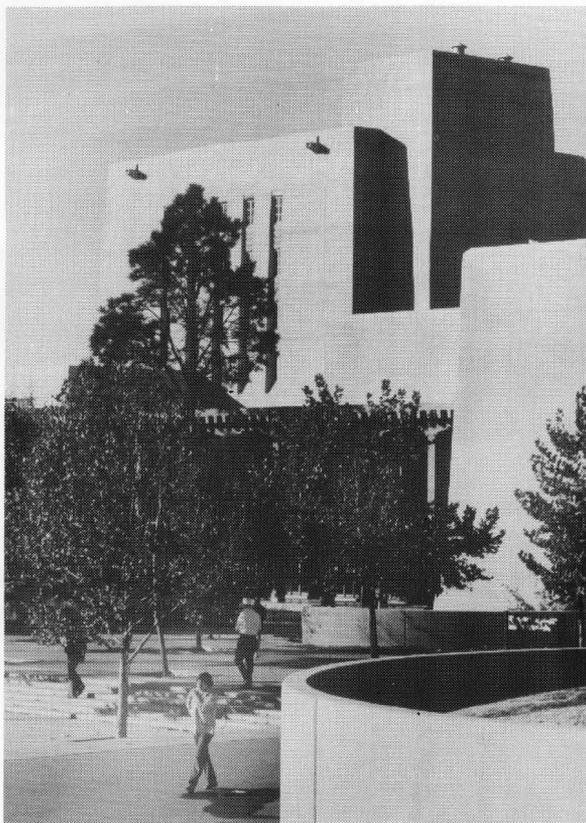
For graduate admission information, call:  
201-596-3460 □ In NJ: 1-800-222-NJIT.  
New Jersey Institute of Technology  
University Heights, Newark, NJ 07102

NJIT does not discriminate on the basis of sex, race, handicap, national or ethnic origin or age in the administration of student programs

# The University of New Mexico

## Research Areas

Toxic and radioactive waste management  
Superconducting ceramics  
Microelectronics processing  
Heterogeneous catalysis  
Laser-enhanced CVD  
Sol-gel and colloidal processing of ceramics  
Biomedical engineering  
Plasma science  
Surface science  
Aerosol physics  
Materials characterization  
Uncertainty and risk assessment



## Faculty

Harold Anderson  
C. Jeffrey Brinker  
Abhaya K. Datye  
David Kauffman  
Toivo T. Kodas  
Richard W. Mead  
H. Eric Nuttall  
Douglas M. Smith  
Ebtisam S. Wilkins

The **University of New Mexico** along with **Sandia and Los Alamos National Laboratories**, and local industry, make Albuquerque a major scientific and research center. The chemical engineering department houses the NSF-supported **Center for Micro-Engineered Ceramics** and the DOE sponsored **Waste Management Education and Research Consortium**. Faculty participate in the **SEMATECH Center of excellence in semiconductor research**, **The Center for High Technology Materials**, and the **Institute for Space Nuclear Power Studies**.

The Chemical Engineering Department offers financial aid in the form of research assistantships paying \$10-15,000 per year, plus tuition. Outstanding students may apply for UNM/National Laboratory fellowships that start at \$15,000/year and involve cooperative research at the national laboratories.

Albuquerque's southwestern climate and rugged mountainous terrain provide plenty of opportunities for outdoor recreation such as skiing, hiking, and whitewater rafting.

**For more information, write to:**  
Douglas M. Smith, Graduate Advisor  
Department of Chemical and Nuclear Engineering  
The University of New Mexico  
Albuquerque, NM 87131-1341

# NORTH CAROLINA STATE UNIVERSITY

## DEPARTMENT OF CHEMICAL ENGINEERING

Box 7905 • North Carolina State University • Raleigh, North Carolina 27695-7905

The Department as a whole has developed a concentration in four broad areas: biochemical engineering, environmental research, microelectronics processing, and polymer science and engineering. Research in each of these areas is characterized by a strong collaboration between departmental faculty, faculty and students from other departments and universities, and, frequently, industrial research groups. This diversity affords students a range of research opportunities, from fundamental to applied. The particular areas of research interests of the faculty are listed below.

### ● FACULTY AND THEIR RESEARCH INTERESTS ●

- Ruben G. Carbonell** (Princeton) *Multi-Phase Transport Phenomena; Bioseparations; Colloid and Surface Science*
- Peter S. Fedkiw** (Berkeley) *Electrochemical Engineering*
- Richard M. Felder** (Princeton) *Computer-Aided Manufacturing of Specialty Chemicals; Process Simulation and Optimization*
- James K. Ferrell** (NC State) *Waste Minimization; Heat Transfer; Process Control*
- Benny D. Freeman** (Berkeley) *Polymer Physical Chemistry*
- Christine S. Grant** (Georgia Tech) *Surface Science; Electrokinetic Separations*
- Carol K. Hall** (Stony Brook) *Statistical Thermodynamics; Bioseparations; Semiconductor Interfaces*
- Harold B. Hopfenberg** (MIT) *Transport and Aging in Glassy Polymers; Controlled Release; Membranes; Barrier Packaging*
- Robert M. Kelly** (NC State) *Microorganisms and Biocatalysis at Elevated Temperatures*
- Peter K. Kilpatrick** (Minnesota) *Interfacial and Surfactant Science; Bioseparations*
- H. Henry Lamb** (Delaware) *Heterogeneous Catalysis; Microelectronics; Surface Science*
- P. K. Lim** (Illinois) *Interfacial Phenomena; Homogeneous Catalysis; Free Radical Chemistry*
- David F. Ollis** (Stanford) *Biochemical Engineering; Heterogeneous Photocatalysis*
- Michael R. Overcash** (Minnesota) *Improving Manufacturing Productivity by Waste Reduction; Environmental*
- Gregory N. Parsons** (N.C. State - Physics) *Electronic Materials; Flat Panel Displays*
- Steven W. Peretti** (Caltech) *Genetic and Metabolic Engineering; Microbial, Plant and Animal Cell Culture*
- George W. Roberts, Head** (MIT) *Heterogeneous Catalysis; Reaction Kinetics and Engineering*
- C. John Setzer, Assoc. Head** (Ohio State) *Plant and Process Economics and Management*
- Vivian T. Stannett** (Brooklyn Poly) *Pure and Applied Polymer Science*

Inquiries to: Professor Peter K. Kilpatrick, Director of Graduate Studies, (919) 737-7121

# Chemical Engineering at

---



# Northwestern University

- S. George Bankoff**, Ph.D., Purdue, 1955  
*Two-phase heat transfer, fluid mechanics*
- Wesley R. Burghardt**, Ph.D., Stanford, 1990  
*Polymer science, rheology*
- John B. Butt**, D.Eng., Yale, 1960  
*Chemical reaction engineering*
- Stephen H. Carr**, Ph.D., Case Western Reserve, 1970  
*Solid state properties of polymers*
- Buckley Crist, Jr.**, Ph.D., Duke, 1966  
*Polymer science*
- Joshua S. Dranoff**, Ph.D., Princeton, 1960  
*Chemical reaction engineering, chromatographic separations*
- Thomas K. Goldstick**, Ph.D., Berkeley, 1966  
*Biomedical engineering, oxygen transport in the human body*
- Harold H. Kung**, Ph.D., Northwestern, 1974  
*Kinetics, heterogeneous catalysis*
- Richard S. H. Mah**, Ph.D., London, 1961  
*Computer-aided process planning, design and analysis*
- William M. Miller**, Ph.D., Berkeley, 1987  
*Biochemical engineering*
- Lyle F. Mockros**, Ph.D., Berkeley, 1962  
*Biomedical engineering, fluid mechanics in biological systems*
- Julio M. Ottino**, Ph.D., Minnesota, 1979  
*Fluid mechanics, chaos, mixing in materials processing*
- E. Terry Papoutsakis**, Ph.D., Purdue, 1980  
*Biochemical engineering*
- Mark A. Petrich**, Ph.D., Berkeley, 1987  
*Environmental engineering, electronic materials, solid state NMR*
- Gregory Ryskin**, Ph.D., Caltech, 1983  
*Fluid mechanics, computational methods, polymeric liquids*
- Wolfgang M. H. Sachtler**, Dr. rer.nat., Braunschweig, 1952  
*Heterogeneous catalysis*
- John M. Torkelson**, Ph.D., Minnesota, 1983  
*Polymer science, membranes*



---

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

Director of Graduate Admissions  
Department  
of Chemical Engineering  
McCormick School of Engineering  
and Applied Science  
Northwestern University  
Evanston, Illinois 60208-3120

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# Chemical Engineering

## at Notre Dame

The University of Notre Dame offers programs of graduate study leading to the Master of Science and Doctor of Philosophy degrees in Chemical Engineering. The requirements for the master's degree are normally completed in sixteen to twenty-four months. The doctoral program requires about four years of full-time study beyond the bachelor's degree. These programs can usually be tailored to accommodate students whose undergraduate degrees are in areas of science or engineering other than chemical engineering.

Financially attractive fellowships and assistantships, which include a full tuition waiver, are available to students pursuing either program.



### FACULTY

J. T. Banchemo  
J. F. Brennecke  
J. J. Carberry  
H. -C. Chang  
D. A. Hill  
J. C. Kantor  
J. P. Kohn  
D. T. Leighton, Jr.  
M. J. McCready  
R. A. Schmitz  
W. C. Strieder  
A. Varma  
E. E. Wolf

### RESEARCH AREAS

Advanced Ceramic Materials  
Artificial Intelligence  
Catalysis and Surface Science  
Chemical Reaction Engineering  
Gas-Liquid Flows  
Nonlinear Dynamics  
Phase Equilibria  
Polymer Science  
Process Dynamics and Control  
Statistical Mechanics  
Supercritical Fluids  
Suspension Rheology  
Thermodynamics and Separations  
Transport Phenomena

**For further information, write to:**

Dr. D. T. Leighton, Jr. • Department of Chemical Engineering  
University of Notre Dame • Notre Dame, Indiana 46556





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- *Excellent facilities and a unique combination of research projects at the frontiers of science and technology.*
- *Outstanding faculty and student body who are both dedicated and professional.*
- *Attractive campus only minutes away from newly-revitalized downtown Columbus.*
- *Financial support ranging from \$12,000 to \$16,000 annually, plus tuition.*

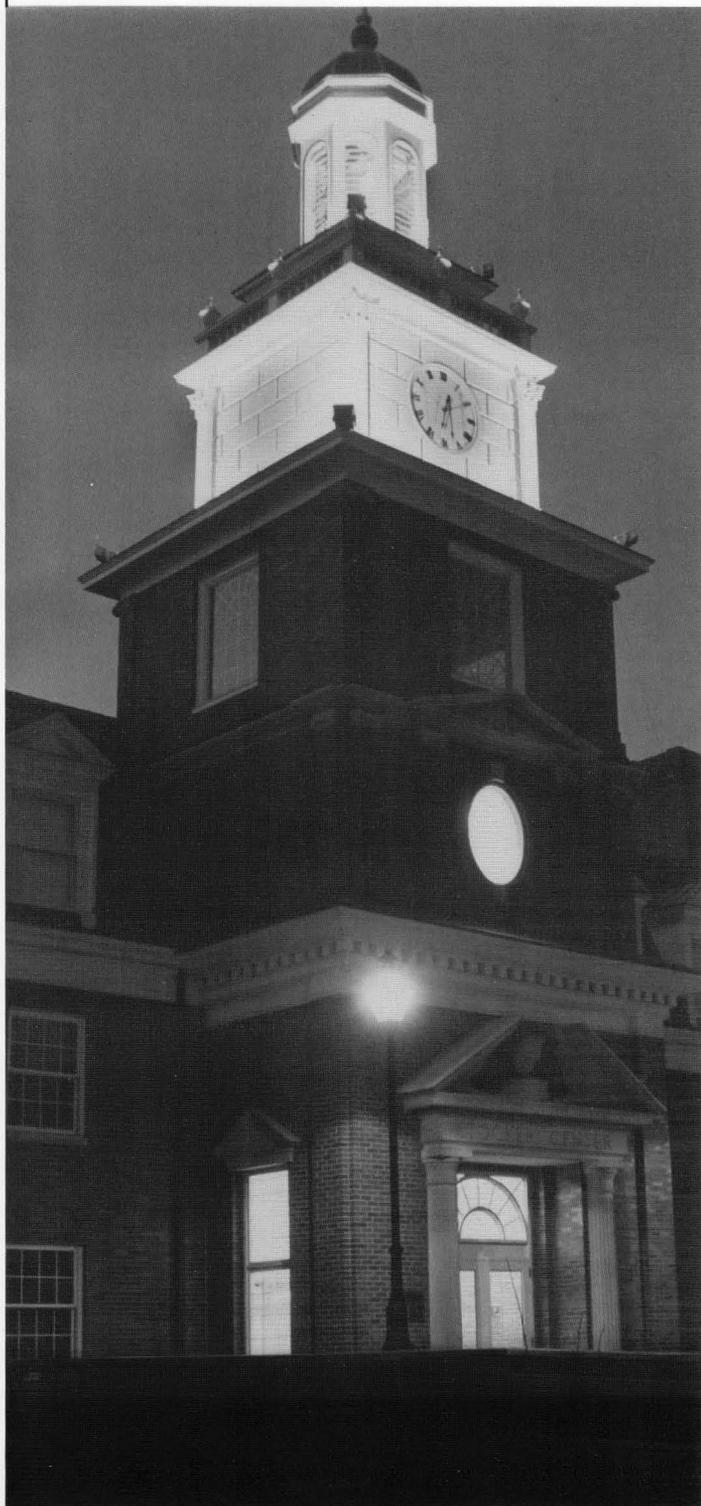
For complete information on our programs, potential thesis topics, and degree requirements write or call collect: Professor Jacques L. Zakin, Chairperson, Department of Chemical Engineering, The Ohio State University, 140 W. 19th Avenue, Columbus, Ohio 43210-1180, (614) 292-6986.

- 
- **Robert S. Brodkey**, *Wisconsin 1952*, Turbulence, Mixing, Image Analysis, Reactor Design, and Rheology
  - **Jeffrey J. Chalmers**, *Cornell 1988*, Biochemical Engineering, Protein Excretion and Production, and Immobilized Cell Reactor Design
  - **James F. Davis**, *Northwestern 1981*, Artificial Intelligence, Process Control and Computer-Aided Design
  - **L. S. Fan**, *West Virginia 1975*, Fluidization, Powder Technology, Multiphase and Particulates Reaction Engineering, and Mathematical Modeling
  - **Morton H. Friedman**, *Michigan 1961*, Biomedical Engineering and Hemodynamics
  - **Harry C. Hershey**, *Missouri-Rolla 1965*, Thermodynamics and Drag Reduction
  - **Kurt W. Koelling**, *Princeton 1992*, Polymer Processing, Liquid Crystalline Polymers, Biodegradable Polymers, Polymer Rheology and Morphology
  - **L. James Lee**, *Minnesota 1979*, Polymer Processing, Polymerization, and Rheology
  - **Won-Kyoo Lee**, *Missouri-Columbia 1972*, Process Control, Computer Control, and Computer-Aided Design
  - **Umit S. Ozkan**, *Iowa State 1984*, Application of Heterogeneous Catalysis to Energy and Environmental Issues, Catalytic Materials, and Heterogeneous Kinetics
  - **James F. Rathman**, *Oklahoma 1987*, Interfacial Phenomena, Surfactant Science, Rheology of Surfactant Systems
  - **David L. Tomasko**, *Illinois 1992*, Intermolecular Interactions in Supercritical Fluids, Supercritical Fluid Extraction
  - **Shang-Tian Yang**, *Purdue 1984*, Biochemical Engineering and Biotechnology, Fermentation Processes, and Kinetics
  - **Jacques L. Zakin**, *New York 1959*, Surfactant and Polymer Drag Reduction, Rheology, and Emulsions

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*The Ohio State University is an equal opportunity/affirmative action institution.*

# Chemical Engineering



## Graduate Programs

The Department of Chemical Engineering offers programs leading to both the M.S. and Ph.D. degrees. The department is located in the Stocker Engineering Center, which recently (1985) underwent extensive modernization and now contains some of the finest state-of-the-art equipment available. The department's activities are enhanced by the Stocker endowment, which was made possible by the generosity of Dr. C. Paul and Beth K. Stocker and which has now grown to over \$14 million. The interest on this endowment is used to help support research efforts in such ways as providing competitive graduate fellowships and associateships, matching equipment funds, and seed money for new project areas.

## Research Areas

Multiphase Flow and Associated Corrosion  
Coal Conversion Technology and Desulfurization  
Aerosol Science and Technology  
Process Control  
Transport Processes and Modelling  
Separations  
Energy and Environmental Engineering  
Thin Film Materials  
Metallic Corrosion  
Chemical Reaction Engineering  
Wastewater Treatment  
Bioreactor Analysis  
Downstream Processing of Proteins

## Financial Aid

Financial support includes teaching and grant-related associateships and fellowships ranging from \$10,000 to \$15,000 per twelve months. In addition, students are granted a full tuition scholarship for both the regular and summer academic terms. Stocker Fellowships are available to especially well-qualified students.

## The Faculty

William D. Baasel, P.E. (Ph.D., Cornell, 1962)  
Calvin H. Baloun, P.E. (Ph.D., Cincinnati, 1962)  
W. J. Russell Chen (Ph.D., Syracuse, 1974)  
Nicholas Dinos (Ph.D., Lehigh, 1967)  
Tingyue Gu (Ph.D., Purdue, 1991)  
Daniel A. Gulino (Ph.D., Illinois, 1983)  
W. Paul Jepson, Chair (Ph.D., Heriot-Watt, 1980)  
H. Benne Kendall, P.E., Emeritus (Ph.D., Case Institute of Technology, 1956)  
Michael E. Prudich (Ph.D., West Virginia, 1979)  
Darin Ridgway, P.E. (Ph.D., Florida State, 1990)  
Kendree J. Sampson (Ph.D., Purdue, 1981)  
Robert L. Savage, P.E., Emeritus (Ph.D., Case Institute of Technology, 1948)

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**For More Information:** Director of Graduate Studies,  
Department of Chemical Engineering, 172 Stocker Center,  
Ohio University, Athens OH 45701-2979

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Or write:

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School of Chemical Engineering  
& Materials Science  
The University of Oklahoma  
100 E. Boyd, Room T-335  
Norman, Oklahoma 73019-0628



The University of Oklahoma  
is an Equal Opportunity Institution

## CEMS Faculty & Their Research Interests

**Billy L. Crynes, Professor; Dean, College of Engineering.**

*Chemical Engineering:* • Modeling of hydrocarbon pyrolysis  
• Surface effects during pyrolysis of hydrocarbons

**Raymond D. Daniels, Professor. Metallurgical Engineering:**

• physical metallurgy • gases in metals • corrosion  
• metal fracture

**Roger G. Harrison, Jr., Associate Professor. Chemical**

*Engineering:* • production of proteins and peptides using recombinant DNA technology • separation and purification of biochemicals • enzyme reactors • protein engineering • drug delivery systems • applications of biotechnology to waste treatment

**Jeffrey H. Harwell, Professor and Director. Chemical Engineering:**

• tertiary oil recovery • unconventional low energy separation processes • mass transfer • dynamics of multicomponent mass transfer processes • surface phenomena • adsorption kinetics

**Lloyd L. Lee, Professor. Chemical Engineering:**

• thermodynamics • molecular transport theory  
• statistical mechanics • structured liquids • Monte Carlo and molecular dynamics studies • conformal solution theory • natural gas properties • polar fluids, ionic solutions and molten salts • surface adsorption  
• turbulent flow • polymer processing, spinning, extrusion and coating

**Lance L. Lobban, Assistant Professor. Chemical Engineering:**

• catalytic reaction rate mechanisms and modeling  
• partial oxidation of hydrocarbons • synthesis of refractory powders

**Richard G. Mallinson, Associate Professor. Chemical Engineering:**

• chemical, catalytic and biomedical rate processes  
• synthetic fuels

**Matthias U. Nollert, Assistant Professor. Chemical Engineering:**

• viscous flow • computational fluid mechanics  
• suspension rheology • mammalian cell physiology  
• endothelium/blood interactions • thrombosis and fibrinolysis • hematopoiesis

**Edgar A. O'Rear, III, Professor. Chemical Engineering:**

• catalysis • surface chemistry and physics • kinetics  
• blood trauma associated with medical devices  
• biorheology • organic chemistry • coal technology

**John F. Scamehorn, George Lynn Cross Research Professor.**

*Chemical Engineering:* • surface and colloid science  
• tertiary oil recovery • detergency • membrane separations • adsorption • pollution control • polymers

**Robert L. Shambaugh, Associate Professor. Chemical Engineering:**

• polymerization chemistry • polymer processing technology • fiber spinning, texturing and extrusion  
• wastewater engineering • physicochemical treatment  
• biological treatment • ozonation • gas-liquid reactions

**Kenneth E. Starling, George Lynn Cross Research Professor.**

*Chemical Engineering:* • equation of state development and prediction of thermodynamic and phase behavior • equilibrium and non-equilibrium molecular theory of fluids • correlation of transport properties • process simulation • low temperature difference cycles • geothermal, ocean thermal, solar and wastewater heat energy conversion

# Oklahoma State University

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### Faculty

Kenneth J. Bell (Ph.D., University of Delaware)  
Gary L. Foutch (Ph.D., University of Missouri-Rolla)  
K.A.M. Gasem (Ph.D., Oklahoma State University)  
Martin S. High (Ph.D., Pennsylvania State University)  
A.J. Johannes (Ph.D., University of Kentucky)  
Robert L. Robinson, Jr. (Ph.D., Oklahoma State University)  
D. Alan Tree (Ph.D., University of Illinois)  
Jan Wagner (Ph.D., University of Kansas)  
James R. Whiteley (Ph.D., Ohio State University)

### Research Areas



Adsorption  
Air Pollution  
Biochemical Processes  
Corrosion  
Design  
Fluid Flow  
Gas Processing  
Ground Water Quality  
Hazardous Wastes  
Heat Transfer  
Ion Exchange  
Kinetics and Catalysis  
Mass Transfer  
Modeling  
Phase Equilibria  
Polymers  
Process Simulation  
Thermodynamics

#### **For more information contact**

Graduate Coordinator  
School of Chemical Engineering  
Oklahoma State University  
Stillwater, OK 74078

# OREGON STATE UNIVERSITY

## *Chemical Engineering*

### *M.S. and Ph.D. Programs*

*Our programs reflect not only traditional chemical engineering fields but also new technologies important to the Northwest's industries, such as electronic material processing, forest products, food science, and ocean products.*

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## **FACULTY**

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|------------------------|---|---|
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| <b>T. M. Grace</b>     | • | Chemical Recovery Technology                              |
| <b>M.K. Iisa</b>       | • | Combustion, Waste Minimization                            |
| <b>G. N. Jovanovic</b> | • | Fine Particle Processing, Transport Phenomena             |
| <b>S. Kimura</b>       | • | Reaction Engineering, High-Temperature Materials          |
| <b>J. G. Knudsen</b>   | • | Heat Transfer   |
| <b>M. D. Koretsky</b>  | • | Electronic Materials Processing                           |
| <b>O. Levenspiel</b>   | • | Fluidization, Chemical Reaction Engineering               |
| <b>K. L. Levien</b>    | • | Process Optimization and Control                          |
| <b>J. McGuire</b>      | • | Protein Adsorption, Biofilm Development                   |
| <b>G. L. Rorrer</b>    | • | Biochemical Reaction Engineering                          |
| <b>R. D. Sproull</b>   | • | Biochemical and Environmental Engineering                 |
| <b>J. D. Way</b>       | • | Membrane-Based Separation Processes                       |
| <b>C. E. Wicks</b>     | • | Mass Transfer   |

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*For further information, write:*

Chemical Engineering Department  
Oregon State University • Gleeson Hall, Room 103  
Corvallis, Oregon 97331-2702



## University of Pennsylvania Chemical Engineering

---

**Stuart W. Churchill**

*Combustion, thermoacoustic convection, Czochralski crystallization, rate processes*

**Russell J. Composto**

*Polymeric materials science, surface and interface studies*

**Gregory C. Farrington**

*Electrochemistry, solid state and polymer chemistry*

**William C. Forsman**

*Polymer science and engineering, graphite intercalation*

**Eduardo D. Glandt**

*Classical and statistical thermodynamics, random media*

**Raymond J. Gorte**

*Heterogeneous catalysis, surface science, zeolites*

**David J. Graves**

*Biochemical and biomedical engineering, bioseparations*

**Mitchell Litt**

*Biorheology, transport processes in biological systems, biomedical engineering*

**Alan L. Myers**

*Adsorption of gases and liquids, molecular simulations*

**Daniel D. Perlmutter**

*Chemical reactor design, gas-solid reactions, gel kinetics*

**John A. Quinn**

*Membrane transport, biochemical/biomedical engineering*

**Warren D. Seider**

*Process analysis, simulation, design, and control*

**Lyle H. Ungar**

*Artificial intelligence in process control, neural networks*

**T. Kyle Vanderlick**

*Thin-film and interfacial phenomena*

**John M. Vohs**

*Surface science and heterogeneous catalysis*

**Paul B. Weisz**

*Molecular selectivity in chemical and life processes*

*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. The cultural advantages, historical assets, and recreational facilities of a great city are within walking distance of the University.*

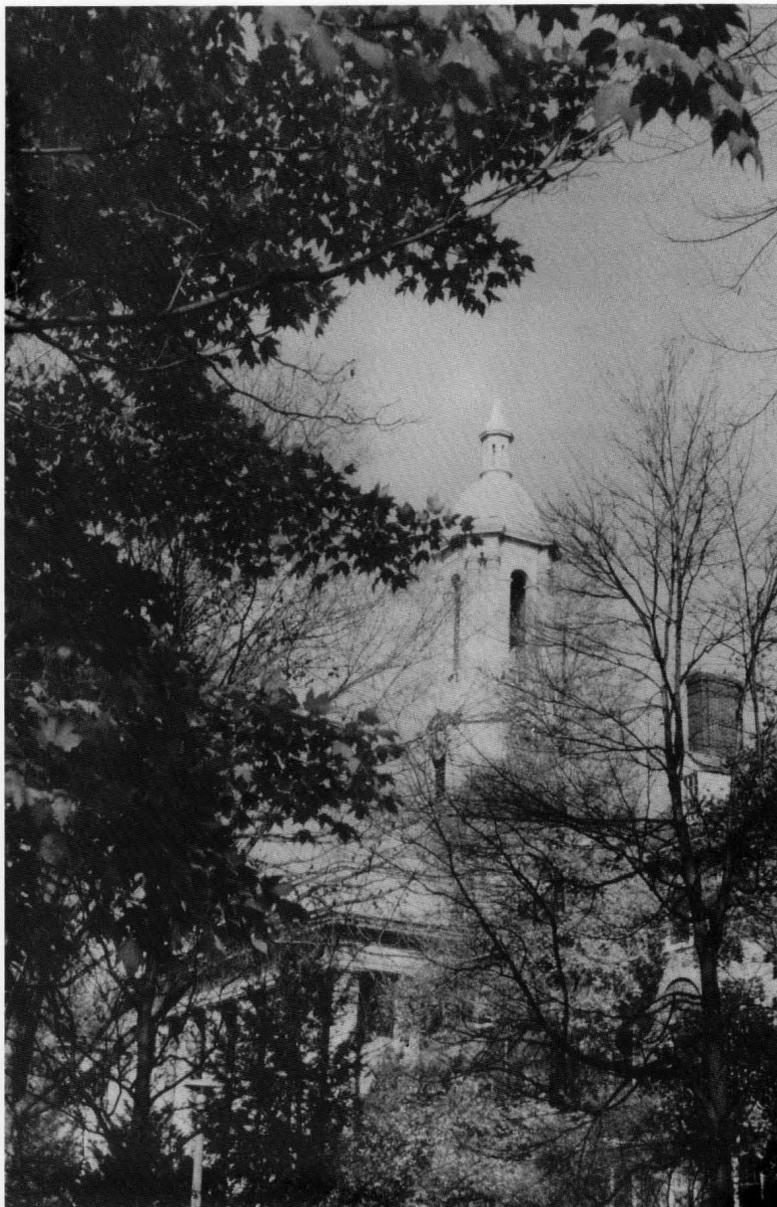
---

**For additional information, write:**

Director of Graduate Admissions  
Department of Chemical Engineering  
311A Towne Building  
University of Pennsylvania  
Philadelphia, Pennsylvania 19104-6393



# PENN STATE



Individuals holding the B.S. in chemistry or other related areas are encouraged to apply.

For more information, contact  
Chairman, Graduate Admissions Committee  
The Pennsylvania State University  
Department of Chemical Engineering  
158 Fenske Laboratory  
University Park, PA 16802

**Paul Barton** (Penn State)  
*Separational Processes*

**Ali Borhan** (Stanford)  
*Fluid Dynamics, Transport Phenomena*

**Alfred Carlson** (Wisconsin)  
*Biotechnology, Bioseparations*

**Lance R. Collins** (Penn)  
*Turbulent Flow, Combustion*

**Wayne Curtis** (Purdue)  
*Plant Biotechnology*

**Ronald P. Danner** (Lehigh)  
*Applied Thermodynamics, Adsorption Phenomena*

**Thomas E. Daubert** (Penn State)  
*Applied Thermodynamics*

**J. Larry Duda** (Delaware)  
*Polymers, Diffusion, Tribology, Fluid Mechanics, Rheology*

**John A. Frangos** (Rice)  
*Biomedical Engineering, Biotechnology*

**Kristen Fichthorn** (Michigan)  
*Statistical Mechanics, Surface Science, Catalysis*

**William P. Hegarty** (Michigan)  
*Plant Design*

**Arthur E. Humphrey** (Columbia)  
*Biotechnology*

**John R. McWhirter** (Penn State)  
*Gas-Liquid Mass Transfer, Microencapsulation*

**R. Nagarajan** (SUNY Buffalo)  
*Colloid and Polymer Science*

**Jonathan Phillips** (Wisconsin)  
*Heterogeneous Catalysis, Surface Science*

**John M. Tarbell** (Delaware)  
*Cardiovascular Fluid Mechanics and Mass Transfer, Turbulent Reacting Flows*

**James S. Ultman** (Delaware)  
*Mass Transport in the Human Lung, Intensive Care Monitoring*

**M. Albert Vannice** (Stanford)  
*Heterogeneous Catalysis*

**James S. Vrentas** (Delaware)  
*Transport Phenomena, Applied Mathematics, Polymer Science*

**DEGREE PROGRAMS**  
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MS in Bioengineering

# What is chemical engineering at Pitt?

**A short answer:**

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colloidal suspensions  
combustion  
flow through porous media  
heterogeneous catalysis  
kinetics  
microemulsions  
molecular thermodynamics  
organometallic chemistry  
petroleum engineering  
phase equilibria  
polymers  
process design  
protein engineering  
reaction engineering  
recycling technology  
separation science  
solids processing  
superacids  
supercritical fluids  
surface chemistry  
transport phenomena

For a more detailed answer, and information about fellowships and applications, write or call the

**Graduate Coordinator  
Department of Chemical  
and Petroleum Engineering  
1249 Benedum Hall  
University of Pittsburgh  
Pittsburgh, PA 15261  
412-624-9630**

## **FACULTY**

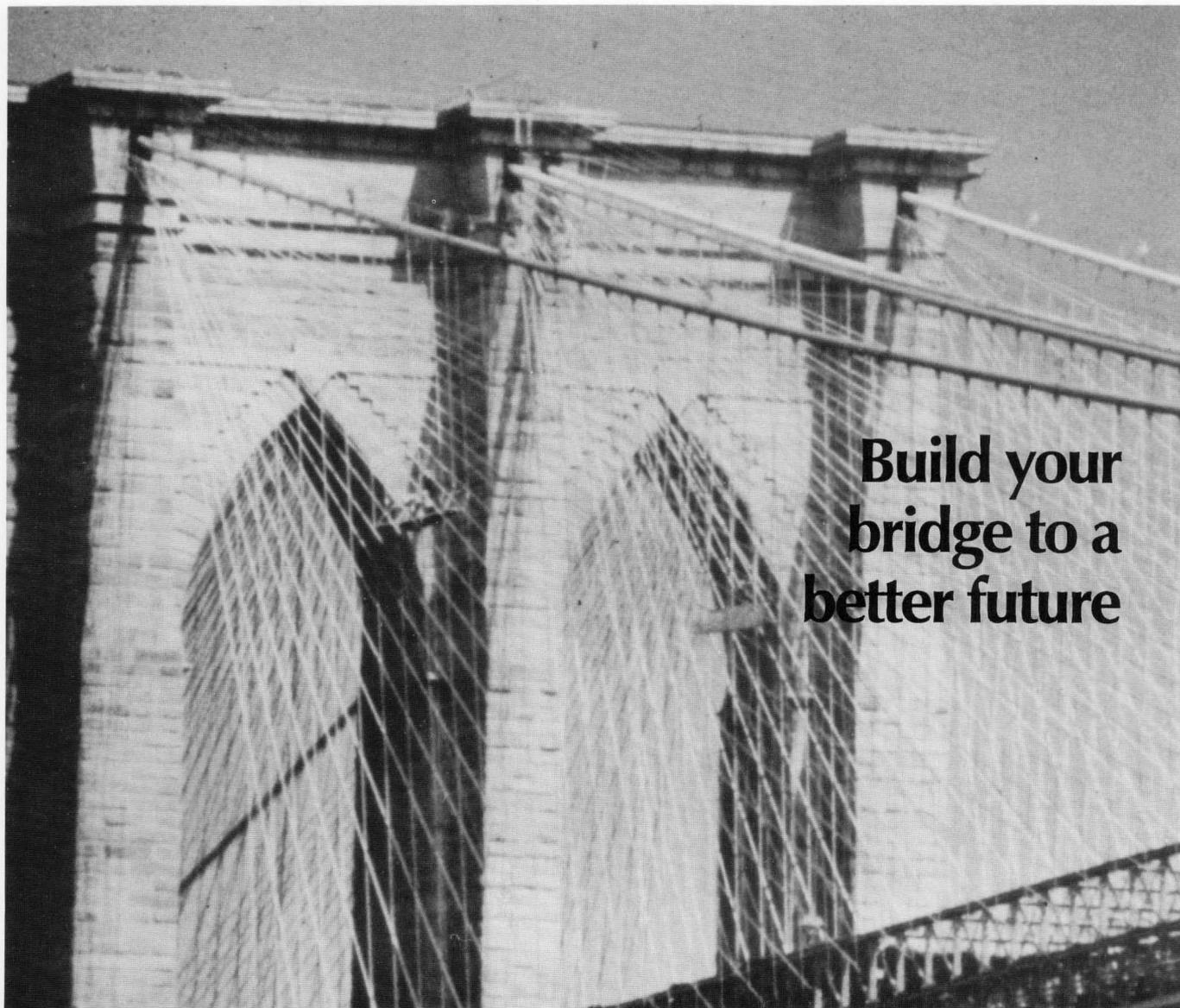
Mohammad M. Ataai	Robert M. Enick	Alan A. Reznik
Eric J. Beckman	Dan Farcasiu	Alan J. Russell
Donna G. Blackmond	James G. Goodwin, Jr.	Jerome S. Schultz
Alan J. Brainard	Gerald D. Holder	Sindee Simon
Edward Cape	George E. Klinzing	John W. Tierney
Shiao-Hung Chiang	George Marcelin	William Wagner
James T. Cobb, Jr.	Badie I. Morsi	Irving Wender
		Joseph Yerulshami



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## Chemical Engineering Graduate Studies at Polytechnic University



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- Faculty ■
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For more information contact:

Professor A.S. Myerson  
Head, Dept. of Chemical Engineering  
Polytechnic University  
333 Jay Street  
Brooklyn, NY 11201  
(718) 260-3620

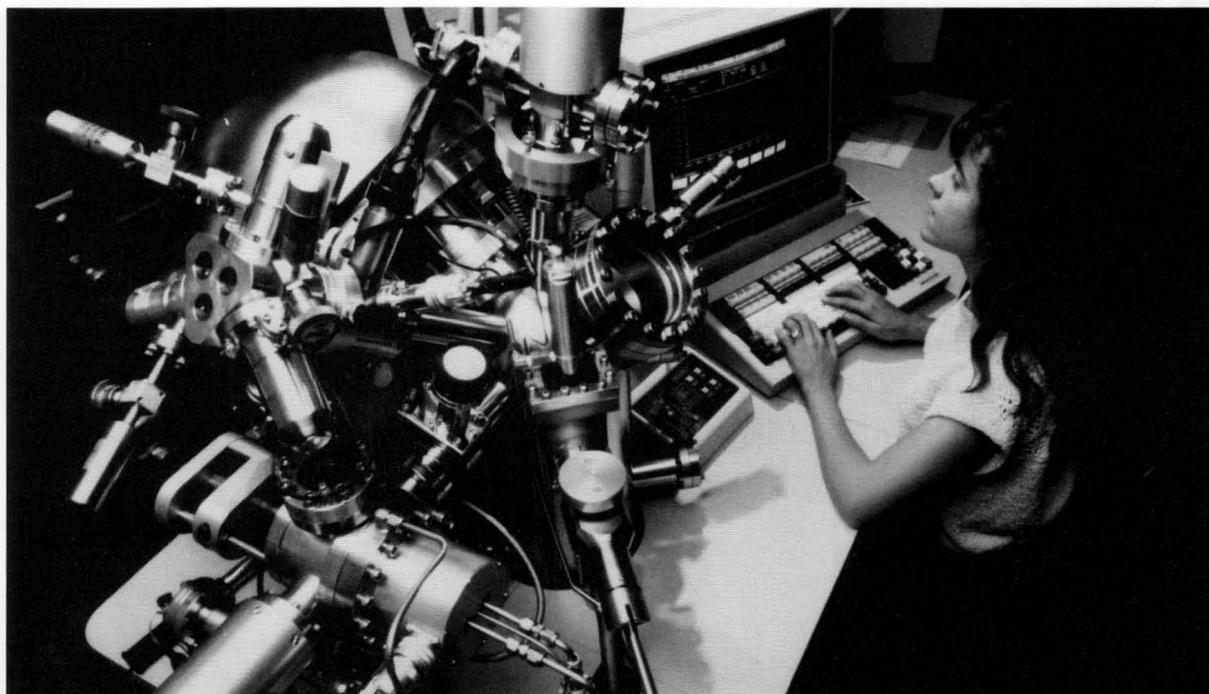
**Polytechnic**  
UNIVERSITY

# Graduate Studies in Chemical Engineering Purdue University



## Faculty

L.F. Albright, *Emeritus*  
R.P. Andres  
J.M. Caruthers  
K.C. Chao  
W.N. Delgass  
F.J. Doyle  
R.E. Eckert  
A.H. Emery  
E.I. Franses  
R.A. Greenkorn  
H.L. Hampsch  
R.E. Hannemann  
R.N. Houze  
D.P. Kessler  
J.F. Pekny  
N.A. Peppas  
D. Ramkrishna  
G.V. Reklaitis  
R.G. Squires  
C.G. Takoudis  
J. Talbot  
G.T. Tsao  
V. Venkatasubramanian  
N.H.L. Wang  
P.C. Wankat  
J.M. Wiest



## Research Areas

- Applied Mathematics
- Artificial Intelligence
- Biochemical Engineering
- Biomedical Engineering
- Catalysis and Reaction Engineering
- Colloids and Interfacial Engineering
- Process Operations and Design
- Environmental Science
- Materials and Microelectronics Processing
- Parallel Computing and Combinatorics
- Polymer Science and Engineering
- Process Control
- Separation Processes
- Surface Science and Engineering
- Thermodynamics and Statistical Mechanics
- Transport Phenomena

### Degrees Offered

Master of Science  
Doctor of Philosophy

### Financial Assistance

Fellowships  
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**For more information about our graduate studies program please contact:**

Graduate Studies  
Purdue University  
1283 Chemical Engineering Building  
West Lafayette, Indiana 47907-1283

Phone: (317) 494-4057





# THE UNIVERSITY OF QUEENSLAND

## Postgraduate Study in Chemical Engineering

*Scholarships Available*

*Return Airfare Included*

### ■ Staff

P. R. Bell (New South Wales)  
I. T. Cameron (Imperial College)  
C. A. Crosthwaite (Queensland)  
D. D. Do (Queensland)  
R. U. Edgehill (Cornell)  
P. F. Greenfield (New South Wales)  
M. R. Johns (Massey)  
P. L. Lee (Monash)  
A. A. Krol (Queensland)  
J. D. Litster (Queensland)  
M. E. Mackay (Illinois)  
D. A. Mitchell (Queensland)  
R. B. Newell (Alberta)  
D. J. Nicklin (Cambridge)  
S. Reid (Griffith)  
V. Rudolph (Natal)  
B. R. Stanmore (Manchester)  
E. T. White (Imperial College)  
R. J. Wiles (Queensland)

### ■ Adjunct Staff

D. Barnes (Birmingham)  
J. M. Burgess (Edinburgh)  
W. W. Eckenfelder (Manhattan)  
J. E. Hendry (Wisconsin)  
G. W. Pace (MIT)  
D. H. Randerson (New South Wales)

### ■ The Department

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

**For further information write to:**

**Co-ordinator of Graduate Studies, Department of Chemical Engineering  
The University of Queensland  
Brisbane Qld 4072 Australia.**



### ■ Research Areas

- Catalysis
- Fluidization
- Systems Analysis
- Computer Control
- Applied Mathematics
- Transport Phenomena
- Crystallization
- Polymer Processing
- Rheology
- Chemical Reactor Analysis
- Energy Resource Studies
- Oil Shale Processing
- Water and Wastewater Treatment
- Particle Mechanics
- Environmental Systems Modeling
- Process Simulation
- Fermentation Systems
- Tissue Culture
- Enzyme Engineering
- Environmental Control
- Process Economics
- Mineral Processing
- Adsorption
- Membrane Processes
- Hybridoma Technology
- Numerical Analysis
- Large Scale Chromatography

### ■ The University and the City

The University is one of the largest in Australia with more than 22,000 students. Brisbane, with a population of about one million, enjoys a pleasant climate and attractive coasts which extend northward into the Great Barrier Reef.



# Rensselaer

---

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

### Advanced Study and Research Areas

- Advanced materials
- Air pollution control
- Biochemical engineering
- Bioseparations
- Fluid-particle systems
- Heat transfer
- High temperature kinetics
- Interfacial phenomena
- Microelectronics manufacturing
- Multiphase flow
- Polymer reaction engineering
- Process control and design
- Separation engineering
- Simultaneous diffusion and chemical reaction
- Thermodynamics
- Transport Processes

For full details write \_\_\_\_\_  
Department Head  
Department of Chemical Engineering  
Rensselaer Polytechnic Institute  
Troy, New York 12180-3590

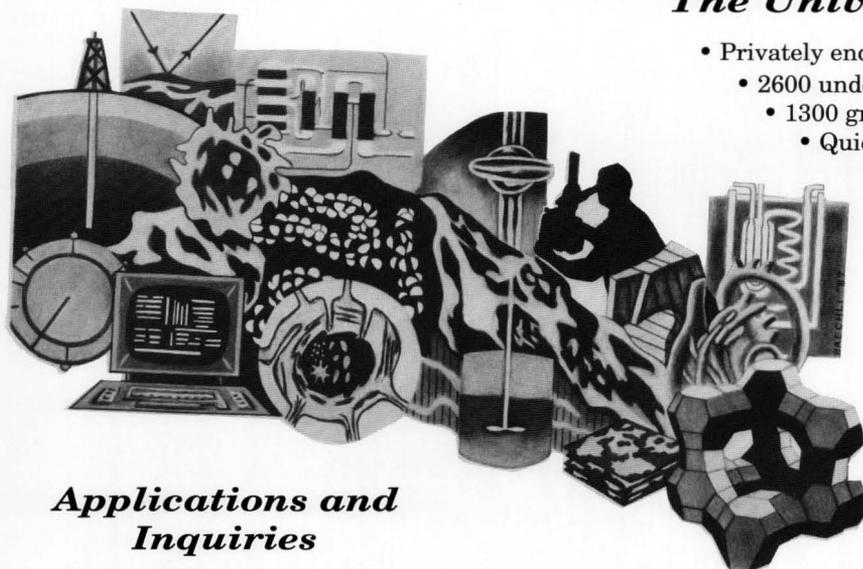
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### The Faculty

Michael M. Abbott *Ph.D., Rensselaer*  
Elmar R. Atwicker *Ph.D., Ohio State*  
Georges Belfort *Ph.D., California—Irvine*  
B. Wayne Bequette *Ph.D., Texas—Austin*  
Henry R. Bungay, III *Ph.D., Syracuse*  
Chan I. Chung *Ph.D., Rutgers*  
Steven M. Cramer *Ph.D., Yale*  
Arthur Fontijn *D.Sc., Amsterdam*  
William N. Gill *Ph.D., Syracuse*  
Martin E. Glicksman *Ph.D., Rensselaer*  
Richard T. Lahey, Jr. *Ph.D., Stanford*  
Howard Littman *Ph.D., Yale*  
Morris H. Morgan, III *Ph.D., Rensselaer*  
Charles Muckenfuss *Ph.D., Wisconsin*  
E. Bruce Nauman *Ph.D., Leeds*  
Joel L. Plawsky *D.Sc., M.I.T.*  
Todd M. Przybycien *Ph.D., Cal. Tech*  
Sanford S. Sternstein *Ph.D., Rensselaer*  
Hendrick C. Van Ness *D.Eng., Yale*  
Peter C. Wayner, Jr. *Ph.D., Northwestern*  
Robert H. Wentorf, Jr. *Ph.D., Wisconsin*

# Rice University

## Graduate Study in Chemical Engineering



### **Applications and Inquiries**

Chairman, Graduate Committee  
Department of Chemical Engineering  
PO Box 1892  
Rice University  
Houston, TX 77251

### **The University**

- Privately endowed coeducational school
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- Architecturally uniform and aesthetic campus

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- Industrial collaboration and job opportunities
- World renowned research and treatment medical center
- Professional sports
- Close to recreational areas

### **The Department**

- M.ChE., M.S., and Ph.D. degrees
- Approximately 65 graduate students (predominantly Ph.D.)
- Stipends and Tuition waivers for full-time students
- Special fellowships with high stipends for outstanding candidates

### **Faculty**

- William W. Akers (*Michigan, 1950*)
- Constantine D. Armeniades (*Case Western Reserve, 1969*)
- Walter Chapman (*Cornell, 1988*)
- Sam H. Davis, Jr. (*MIT, 1957*)
- Derek C. Dyson (*London, 1966*)
- J. David Hellums (*Michigan, 1961*)
- Joe W. Hightower (*Johns Hopkins, 1963*)
- Riki Kobayashi (*Michigan, 1951*)
- Larry V. McIntire (*Princeton, 1970*)
- Antonios G. Mikos (*Purdue, 1988*)
- Clarence A. Miller (*Minnesota, 1969*)
- Mark A. Robert (*Swiss Fed. Inst. of Technology, 1980*)
- Ka-Yiu San (*CalTech, 1984*)
- Jacqueline Shanks (*CalTech, 1989*)
- Kyriacos Zygourakis (*Minnesota, 1981*)

### **Research Interests**

- Applied Mathematics
- Biochemical Engineering
- Biomedical Engineering
- Equilibrium Thermodynamic Properties
- Fluid Mechanics
- Interfacial Phenomena
- Kinetics and Catalysis
- Polymer Science
- Process Control
- Reaction Engineering
- Rheology
- Statistical Mechanics
- Transport Processes
- Transport Properties

# *Chemical Engineering at the* **UNIVERSITY OF ROCHESTER**



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*For further information and application, write*

Professor Harvey J. Palmer, Chair  
Department of Chemical Engineering  
University of Rochester  
Rochester, New York 14627  
Phone: (716) 275-4042  
Fax: (716) 442-6686

## **Faculty and Research Areas**

**S. H. CHEN**, Ph.D. 1981, Minnesota  
*Polymer Science and Engineering, Transport  
Phenomena, Optical Materials*

**E. H. CHIMOWITZ**, Ph.D. 1982, Connecticut  
*Critical Phenomena, Statistical Mechanics of  
Fluids, and Computer-Aided Design*

**M. R. FEINBERG**, Ph.D. 1968, Princeton  
*Complex Reaction Systems, Optimal Reactor  
Design, Applied Mathematics*

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

**J. C. FRIEDLY**, Ph.D. 1965, California (Berkeley)  
*Process Dynamics, Control, Heat Transfer*

**R. H. HEIST**, Ph.D. 1972, Purdue  
*Nucleation, Aerosols, Ultrafine Particles*

**S. A. JENEKHE**, Ph.D. 1985, Minnesota  
*Polymer Science and Engineering, Materials  
Chemistry, Electronic and Optical Materials*  
Fall 1992

**J. JORNE**, Ph.D. 1972, California (Berkeley)  
*Electrochemical Engineering, Microelectronics  
Processing, Theoretical Biology*

**R. H. NOTTER**, Ph.D. 1969, Washington (Seattle)  
M.D. 1980, Rochester  
*Biomedical Engineering, Lung Surfactant,  
Molecular Biophysics*

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

**H. SALTSBURG**, Ph.D. 1955, Boston  
*Surface Phenomena, Catalysis*

**S. V. SOTIRCHOS**, Ph.D. 1982, Houston  
*Reaction Engineering, Gas-Solid Reactions,  
Processing of Ceramic Materials*

**J. H. D. WU**, Ph.D. 1987, M.I.T.  
*Biochemical Engineering, Fermentation,  
Biocatalysis, Genetic and Tissue Engineering*



# RUTGERS

THE STATE UNIVERSITY  
OF NEW JERSEY



## M.S. and Ph.D. PROGRAMS

IN THE DEPARTMENT OF

## CHEMICAL & BIOCHEMICAL ENGINEERING

### AREAS OF TEACHING AND RESEARCH

#### CHEMICAL ENGINEERING FUNDAMENTALS

- THERMODYNAMICS ● TRANSPORT PHENOMENA ● KINETICS AND CATALYSIS ● CONTROL THEORY ● COMPUTERS AND OPTIMIZATION ● POLYMERS AND SURFACE CHEMISTRY ● SEMIPERMEABLE AND LIQUID MEMBRANES ● CHAOTIC FLOWS AND DISORDERED SYSTEMS ● INTERFACIAL ENGINEERING

#### BIOCHEMICAL ENGINEERING FUNDAMENTALS

- MICROBIAL REACTIONS AND PRODUCTS ● SOLUBLE AND IMMOBILIZED BIOCATALYSIS ● BIOMATERIALS ● ENZYME AND FERMENTATION REACTORS ● HYBRIDOMA, PLANT, AND INSECT CELL CULTURES ● INTERDISCIPLINARY BIOTECHNOLOGY ● CELLULAR BIOENGINEERING ● BIOSEPARATIONS

#### ENGINEERING APPLICATIONS

- |                          |                               |                                     |
|--------------------------|-------------------------------|-------------------------------------|
| ● BIOCHEMICAL TECHNOLOGY | ● CHEMICAL TECHNOLOGY         | ● MANAGEMENT OF HAZARDOUS WASTES    |
| • DOWNSTREAM PROCESSING  | • EXPERT SYSTEMS / AI         | • HAZARDOUS & TOXIC WASTE TREATMENT |
| • FOOD PROCESSING        | • ELECTROCHEMICAL ENGINEERING | • WASTEWATER RECOVERY AND REUSE     |
| • GENETIC ENGINEERING    | • STATISTICAL THERMODYNAMICS  | • INCINERATION & RESOURCE RECOVERY  |
| • PROTEIN ENGINEERING    | • TRANSPORT AND REACTION IN   | • MICROBIAL DETOXIFICATION          |
| • IMMUNOTECHNOLOGY       | MULTIPHASE SYSTEMS            | • SOURCE CONTROL AND RECYCLING      |

**FELLOWSHIPS  
AND ASSISTANTSHIPS  
ARE AVAILABLE**

For Application Forms and Further Information, Write, Phone, or FAX to  
Director of Graduate Program  
Department of Chemical and Biochemical Engineering  
Rutgers, The State University of New Jersey  
P.O. Box 909  
Piscataway, NJ 08855-0909  
Phone (908)932-2228 or FAX (908) 932-5313

# The University of South Carolina

## Get to the Point!

### Graduate Studies in

### CHEMICAL ENGINEERING

The University of South Carolina, with its main campus in Columbia, is a comprehensive research university. The new and innovative John E. Swearingen Center houses the College of Engineering and serves as a focal point for much of the research in one of the fastest growing areas in the country.

#### Research Areas

Catalysis	Polymerization Control
Composite Materials	Process Control
Corrosion	Rheology
Electrochemistry	Solvent Extraction
Multiphase Flow	Supercritical Fluids
Phase Equilibria	

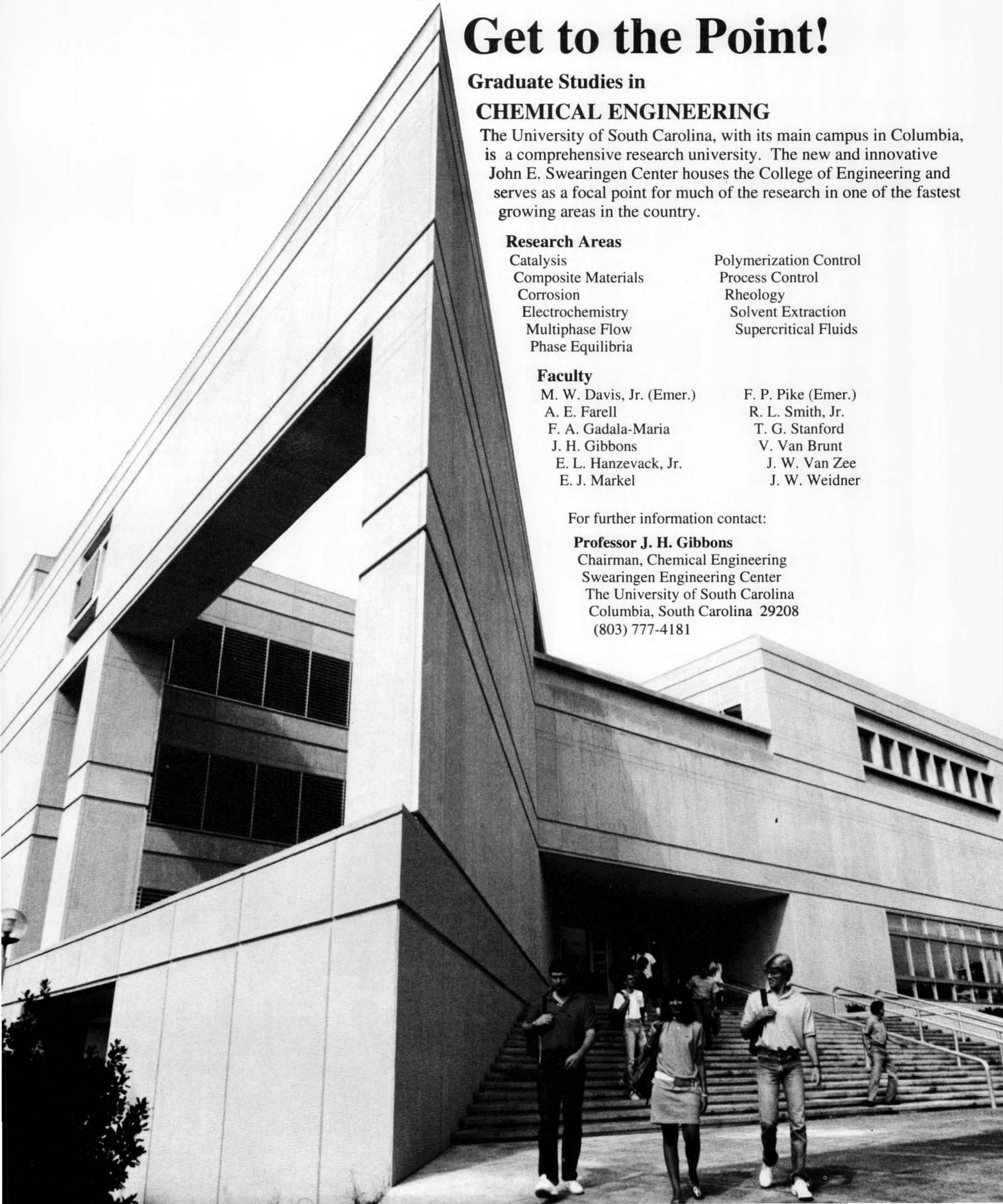
#### Faculty

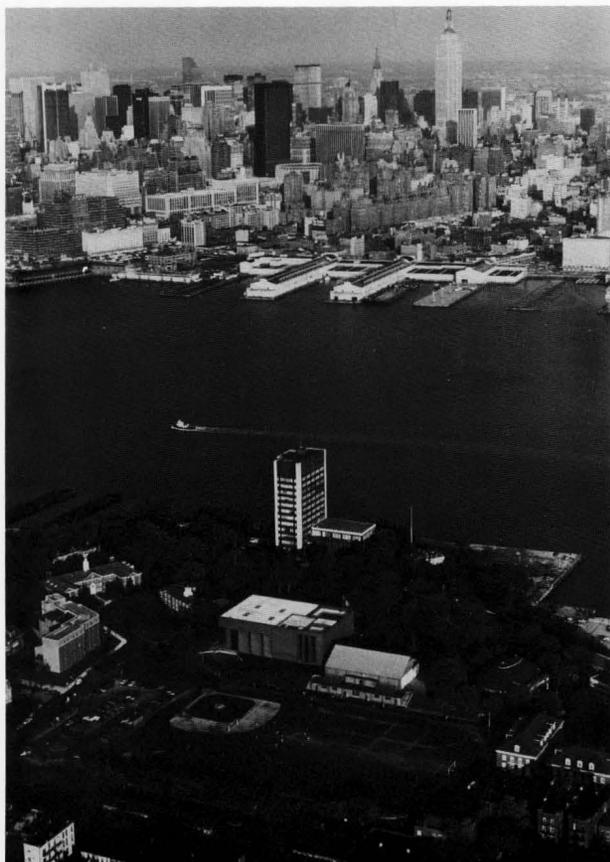
M. W. Davis, Jr. (Emer.)	F. P. Pike (Emer.)
A. E. Farell	R. L. Smith, Jr.
F. A. Gadala-Maria	T. G. Stanford
J. H. Gibbons	V. Van Brunt
E. L. Hanzevack, Jr.	J. W. Van Zee
E. J. Markel	J. W. Weidner

For further information contact:

#### Professor J. H. Gibbons

Chairman, Chemical Engineering  
Swearingen Engineering Center  
The University of South Carolina  
Columbia, South Carolina 29208  
(803) 777-4181





# STEVENS

---

## INSTITUTE OF TECHNOLOGY

- Multidisciplinary department consisting of chemical and polymer engineering, chemistry, and biology
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- Close to the world's center of science and culture
- At the hub of major highways, air, rail, and bus lines
- At the center of the country's largest concentration of research laboratories and chemical, petroleum, pharmaceutical, and biotechnology companies
- Well equipped analytical laboratories, machine, and electronic shops
- One of the leaders in polymer engineering computing

### **Faculty**

---

J. A. Biesenberger (PhD, Princeton University)  
G.B. DeLancey (PhD, University of Pittsburgh)  
C. G. Gogos (PhD, Princeton University)  
D. M. Kalyon (PhD, McGill University)  
S. Kovenklioglu (PhD, Stevens Institute of Technology)  
S. Rivera (PhD, Colorado State University)  
D. H. Sebastian (PhD, Stevens Institute of Technology)  
H. Silla, Head, (PhD, Stevens Institute of Technology)

### **Research in**

---

Separation Processes  
Biochemical Reaction Engineering  
Polymer Reaction Engineering  
Polymer Rheology and Processing  
Polymer Characterization  
Catalysis  
Wastewater Treatment  
Process Design and Development  
Process Control and Identification

## GRADUATE PROGRAMS IN CHEMICAL ENGINEERING

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- **PH.D.**

**For application, contact:**  
Office of Graduate Studies  
Stevens Institute of Technology  
Hoboken, NJ 07030  
201-216-5546

**For additional information, contact:**  
Department of Chemistry and Chemical Engineering  
Stevens Institute of Technology  
Hoboken, NJ 07030  
201-216-5546

*Financial Aid is Available to qualified students.*

Stevens Institute of Technology does not discriminate against any person because of race, creed, color, national origin, sex, age, marital status, handicap, liability for service in the armed forces or status as a disabled or Vietnam era veteran.

# Chemical Engineering at Texas

## Research Interests

Aerosol Physics & Chemistry  
Aqueous Mass Transfer  
Barrier Packaging  
Biochemical & Biomedical  
Engineering  
Biomaterials  
Biosensors  
Catalysis  
Chemical Engineering  
Education  
Chemical Reaction  
Kinetics  
Chemical Vapor  
Deposition  
Colloid & Surface Science  
Combustion  
Crystal Structure & Properties  
Crystallization  
Distillation  
Electrochemistry  
Electronic and Optical  
Materials

## Research Interests (cont'd)

Enhanced Oil Recovery  
Expert Systems  
Fault Detection & Diagnosis  
Flow of Suspensions  
Fluid Mechanics  
Heat Transfer  
Laser Processing  
Liquid Crystalline  
Polymers  
Materials Science  
Membrane Science  
Microelectronics Processing  
Optimization  
Plasma Processing  
Polymer Blends  
Polymer Processing  
Polymer Thermodynamics  
Process Dynamics &  
Control  
Process Modeling &  
Simulation  
Protein & Fermentation  
Engineering  
Reaction Injection Molding  
Separation Processes  
Stack Gas Desulfurization  
Statistical Thermodynamics  
Superconductivity  
Supercritical Fluid Science  
Surface Science  
Thermodynamics

## Faculty

**Joel W. Barlow**  
*Wisconsin*  
**Roger T. Bonnecaze**  
*Caltech*  
**James R. Brock**  
*Wisconsin*  
**Thomas F. Edgar**  
*Princeton*  
**John G. Ekerdt**  
*Berkeley*  
**James R. Fair**  
*Texas*  
**George Georgiou**  
*Cornell*  
**Adam Heller**  
*Hebrew (Jerusalem)*  
**David M. Himmelblau**  
*Washington*  
**Jeffrey A. Hubbell**  
*Rice*  
**Keith P. Johnston**  
*Illinois*  
**William J. Koros**  
*Texas*  
**Douglas R. Lloyd**  
*Waterloo*  
**John J. McKetta**  
*Michigan*  
**C. Buddie Mullins**  
*Caltech*  
**Donald R. Paul**  
*Wisconsin*  
**Robert P. Popovich**  
*Washington*  
**Ilya Prigogine**  
*Brussels*  
**Howard F. Rase**  
*Wisconsin*  
**James B. Rawlings**  
*Wisconsin*  
**Gary T. Rochelle**  
*Berkeley*  
**Isaac C. Sanchez**  
*Delaware*  
**Robert S. Schechter**  
*Minnesota*  
**Hugo Steinfink**  
*Polytechnic (New York)*  
**James E. Stice**  
*Illinois Tech*  
**Isaac Trachtenberg**  
*Louisiana State*  
**Eugene H. Wissler**  
*Minnesota*

THE UNIVERSITY OF TEXAS AT AUSTIN



Inquiries should be sent to:

Graduate Advisor • Department of Chemical Engineering  
The University of Texas • Austin, Texas 78712  
(512) 471-6991



# The University of Toledo

**Graduate study toward the M.S. and Ph.D. Degrees  
Assistantships and Fellowships available.**

## CHEMICAL ENGINEERING FACULTY

**Kenneth J. De Witt**, Professor  
*Ph.D., Northwestern University*  
Transport Phenomena, Mathematical Modeling and  
Numerical Methods

**Ronald L. Fournier**, Associate Professor  
*Ph.D., University of Toledo*  
Transport Phenomena, Thermodynamics,  
Mathematical Modeling and Biotechnology

**Saleh Jabarin**, Professor  
*Ph.D., University of Massachusetts*  
Physical Properties of Polymers, Polymer  
Orientation and Crystallization

**Steven E. LeBlanc**, Associate Professor  
*Ph.D., University of Michigan*  
Dissolution Kinetics, Surface and Colloid  
Phenomena, Controlled Release Technology

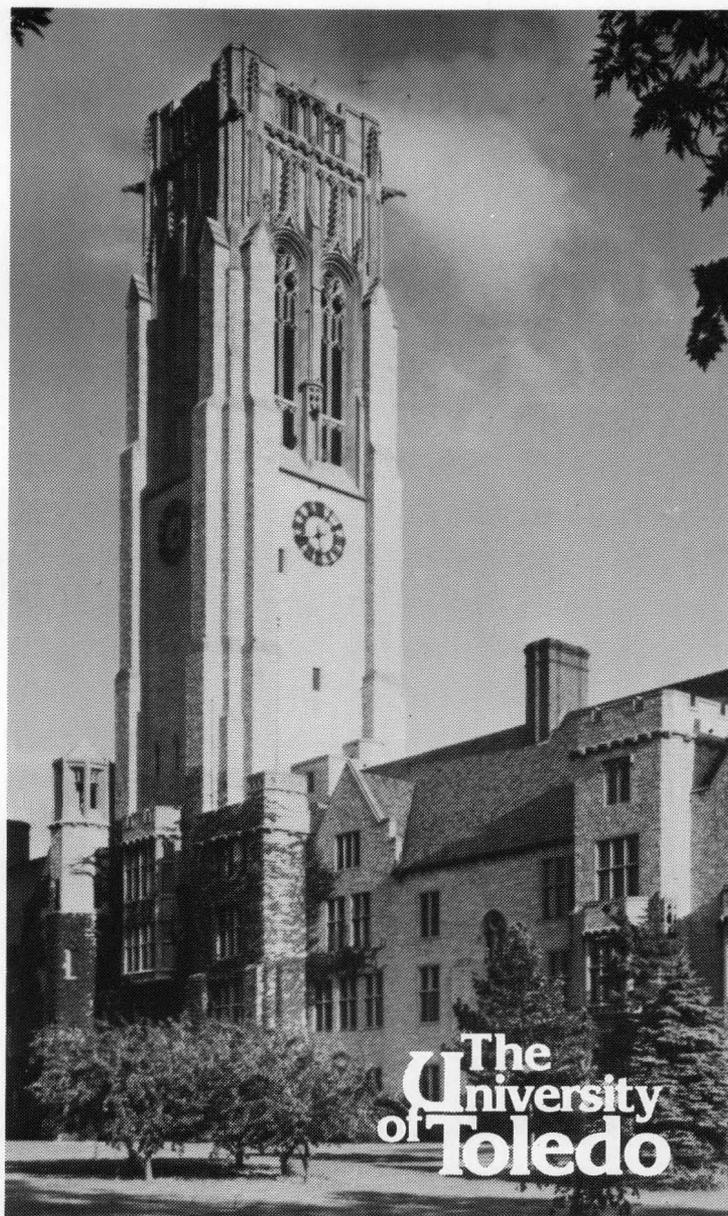
**Richard M. Lemert**, Assistant Professor  
*Ph.D., University of Texas at Austin*  
Thermodynamics and Supercritical Fluid Extraction

**Bruce E. Poling**, Professor, Chairman,  
*Ph.D., University of Illinois*  
Professor; Thermodynamics and Physical  
Properties

**Sasidhar Varanasi**, Associate Professor  
*PhD., State University of New York at Buffalo*  
Colloidal and Interfacial Phenomena, Enzyme  
Kinetics, Membrane Transport

*For Details Contact:*

*Dr. B. E. Poling, Chairman  
Department of Chemical Engineering  
The University of Toledo  
Toledo, OH 43606-3390  
(419) 537-7736*



Regarded as one of the nation's most attractive campuses, The University of Toledo is located in a beautiful residential area of the city approximately seven miles from downtown. The University's main campus occupies more than 200 acres with 40 major buildings. A member of the state university system of Ohio since July 1967, The University of Toledo observed its 100th anniversary as one of the country's major universities in 1972.



# Research Excellence

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◆ You can count on Texas A&M for excellence in engineering graduate studies.

◆ We're one of the top U.S. research universities.

◆ Outstanding faculty bring a strong multi-university background to our chemical engineering programs.

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◆ Call or write for our free video and application/information package: Graduate Advisor, Department of Chemical Engineering, Texas A&M University, College Station, Texas 77843-3122, (409) 845-3361.

◆ Admission to Texas A&M University and any of its sponsored programs is open to qualified individuals.

### ◆ Faculty

**Aydin Akgerman** (University of Virginia, 1971): Separations and Reaction Engineering, Environmental Remediation/Restoration.

**Rayford G. Anthony** (University of Texas, 1966): Catalysis, Reaction Engineering.

**Dragomir B. Bukur** (University of Minnesota, 1974): Reaction Engineering, Catalysis, Multiphase Fluid Flow.

**Jerry A. Bullin** (University of Houston, 1972): Gas Treating and Processing, Roadway Asphalts, Air Quality.

**Bruce E. Dale** (Purdue University, 1979): Biochemical Engineering, Environmental Toxicology.

**Ron Darby** (Rice University, 1962): Rheology, Fluid Mechanics, Transport Phenomena in Non-Newtonian Fluids.

**Richard R. Davison** (Texas A&M University, 1962): Asphalt Chemistry and Technology.

**Leo D. Durbin** (Rice University, 1961): Process Control.

**Philip T. Eubank** (Northwestern University, 1961): Thermodynamics, Plasma Technologies.

**Raymond W. Flumerfelt** (Northwestern University, 1965): Transport Phenomena, Polymers.

**Ahmed M. Gadalla** (Sheffield University, 1964): Advanced Materials and Ceramics.

**Charles J. Glover** (Rice University, 1975): Polymers, Asphalt Characterization.

**Kenneth R. Hall** (University of Oklahoma, 1967): Thermodynamics.

**Daniel T. Hanson** (University of Minnesota, 1967): Biochemical Engineering.

**Charles D. Holland** (Texas A&M University, 1953): Separations Processes, Risk Assessment.

**James C. Holste** (Iowa State University, 1973): Thermodynamics.

**Mark T. Holtzapfel** (University of Pennsylvania, 1981): Biochemical Engineering, Heat Transfer, Refrigeration.

**James C. Liao** (University of Wisconsin, 1987): Cellular Metabolism, Molecular Biology.

**Michael Nikolaou** (University of California-Los Angeles, 1989): Process Control, Modeling.

**Harry J. Ploehn** (Princeton University, 1988): Polymeric and Colloidal Materials, Interfacial Phenomena.

**John C. Slattery** (University of Wisconsin, 1959): Interfacial and Multiphase Transport Phenomena.

**A. Ted Watson** (California Institute of Technology, 1980): Flow Through Porous Media, NMR Imaging.

**Ralph E. White** (University of California-Berkeley, 1977): Electrochemical Engineering, Mathematical Modeling.

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FUNDAMENTALS**

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- MEMBRANE PROCESSES
- CHROMATOGRAPHY
- FACILITATED TRANSPORT
- OPTIMIZATION
- HETEROGENEOUS CATALYSIS
- ELECTROCATALYTIC PROCESSES
- THERMODYNAMICS

**MATERIALS  
AND  
INTERFACES**

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- POLYMER AND FIBER SCIENCE
- CHEMICAL PROCESSING OF HIGH TECH CERAMICS
- PLASMA POLYMERIZATION OF THIN FILMS
- STABILITY OF SUSPENSIONS
- COAL SLURRIES

**BIOCHEMICAL  
AND BIOMEDICAL  
ENGINEERING**

- FERMENTATION TECHNOLOGY
- MAMMALIAN CELL BIOREACTORS
- RECOMBINANT DNA TECHNOLOGY
- APPLIED PHYSIOLOGY
- PROTEIN REFOLDING
- BIOSEPARATIONS

**ENVIRONMENTAL  
ENGINEERING**

- SOLID-WASTE PROCESS ENGINEERING
- HAZARDOUS WASTE TECHNOLOGY
- BIODEGRADATION OF SOLID WASTE
- POLLUTION PREVENTION

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*For information and applications, write to:*

Graduate Committee  
 Department of Chemical Engineering  
 Tufts University  
 Medford, MA 02155  
 Phone (617) 627-3900  
 FAX (617) 627-3991

**FACULTY**

**GREGORY D. BOTSARIS**  
*Ph.D., M.I.T., 1965*

**ELIANA R. DEBERNARDEZ-CLARK**  
*Ph.D., U.N.L. (Argentina), 1984*

**JERRY H. MELDON**  
*Ph.D., M.I.T., 1973*

**JAMES J. NOBLE**  
*Ph.D., M.I.T., 1968*

**DANIEL F. RYDER**  
*Ph.D., Worcester Polytechnic, 1984*

**MICHAEL STOUKIDES**  
*Ph.D., M.I.T., 1982*

**MARTIN V. SUSSMAN**  
*Ph.D., Columbia, 1958*

**NAK-HO SUNG**  
*Ph.D., M.I.T., 1972*

**KENNETH A. VAN WORMER**  
*Sc.D., M.I.T., 1961*

**ADJUNCT FACULTY FROM INDUSTRY**

**FRANCIS BROWN**  
**JOHN R. GHUBLIKIAN**  
**ALAN S. MICHAELS**  
**RANDALL SWARTZ**  
**PARAM H. TEWARI**

# VANDERBILT UNIVERSITY

## Department of Chemical Engineering Graduate Study Leading to the M.S. and Ph.D. Degrees

### **Kenneth A. Debelak (Ph.D., Kentucky)**

*Artificial intelligence in process control; coal conversion with emphasis on particle structure and diffusional processes; hazardous waste minimization.*

### **Tomlinson Fort (Ph.D., Tennessee)**

*Interfacial phenomena in adsorption, thin films, new materials, polymers, tribochemistry, and dispersed systems.*

### **Todd D. Giorgio (Ph.D., Rice)**

*Rheological aspects of blood/endothelial cell response; structured lipid systems; biochemical cell-cell interaction; mechanism and kinetics of cellular ion transport.*

### **Thomas M. Godbold (Ph.D., North Carolina State)**

*Coal pyrolysis and gasification; sulfur removal from syngas; computer-aided design.*

### **David Hunkeler (Ph.D., McMaster)**

*Water soluble polymers and polyelectrolytes, heterophase polymerizations, polymer characterization, light scattering, chromatography, solution properties.*

### **John A. Roth (Ph.D., Louisville)**

*Physical-chemical wastewater treatment; hazardous waste management; corrosion mechanisms in microcircuitry.*

### **Karl B. Schnelle, Jr. (Ph.D., Carnegie Mellon)**

*Environmental dispersion modeling; use of natural gas in atmospheric pollution control; supercritical extraction of toxic materials in the environment.*

### **Eva M. Sevick (Ph.D., Carnegie Mellon)**

*Optical spectroscopy and imaging in strongly scattering media; applications for biomedical imaging, measurement of tissue oxygenation, and characterization of motion and physical properties of colloidal systems.*

### **Robert D. Tanner (Ph.D., Case Western Reserve)**

*Biochemical engineering; effect of light on yeast growth and protein secretion; aerated solid fermentation fluidized bed processes; bubble and aerosol fractionation of proteins.*

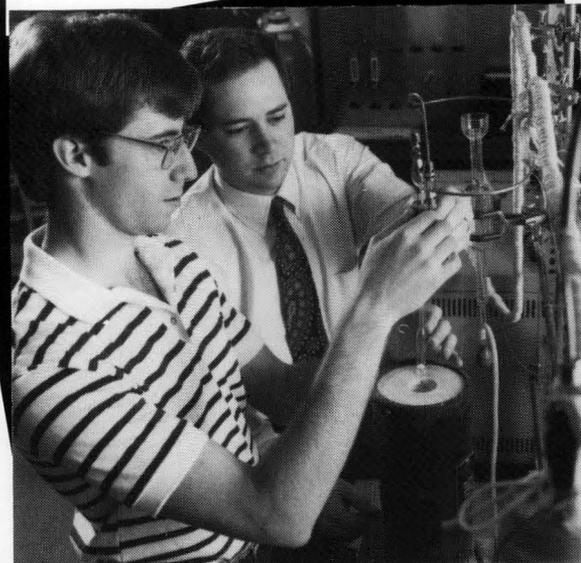
For further information:

**VANDERBILT  
ENGINEERING**



Professor Eva M. Sevick  
Chemical Engineering Department  
Box 1604 Station B  
Vanderbilt University  
Nashville, TN 37235  
1-800-288-7722

University of  
**Virginia**  
Graduate Studies in  
*Chemical Engineering*



**FURTHER INFORMATION**

To receive application materials and further information, please write to

Graduate Admissions Coordinator  
Department of Chemical Engineering  
Thornton Hall  
University of Virginia  
Charlottesville, VA 22903-2442  
Phone: (804) 924 7778

**FACULTY AND RESEARCH AREAS**

**Giorgio Carta** • *Ph.D., University of Delaware* • Absorption, adsorption, ion exchange, biological separations

**Peter T. Cummings** • *Ph.D., University of Melbourne* • Statistical thermodynamics, process design, rheology, bacterial transport

**Robert J. Davis** • *Ph.D., Stanford University* • Heterogeneous catalysis, characterization of metal clusters, reaction kinetics

**Erik J. Fernandez** • *Ph.D., University of California, Berkeley* • Mammalian cell biocatalysis, metabolism in diseased tissues

**Roseanne M. Ford** • *Ph.D., University of Pennsylvania* • Bioremediation, bacterial migration (chemotaxis)

**Elmer L. Gaden, Jr.** • *Ph.D., Columbia University* • Biochemical engineering, bioprocess development and design

**John L. Gainer** • *Ph.D., University of Delaware* • Mass transfer including biomedical applications, biochemical engineering

**John L. Hudson** • *Ph.D., Northwestern University* • Dynamics of chemical reactors, electrochemical and multiphase reactors

**Donald J. Kirwan** • *Ph.D., University of Delaware* • Biochemical engineering, mass transfer, crystallization

**M. Douglas LeVan** • *Ph.D., University of California, Berkeley* • Adsorption, fluid mechanics, process design

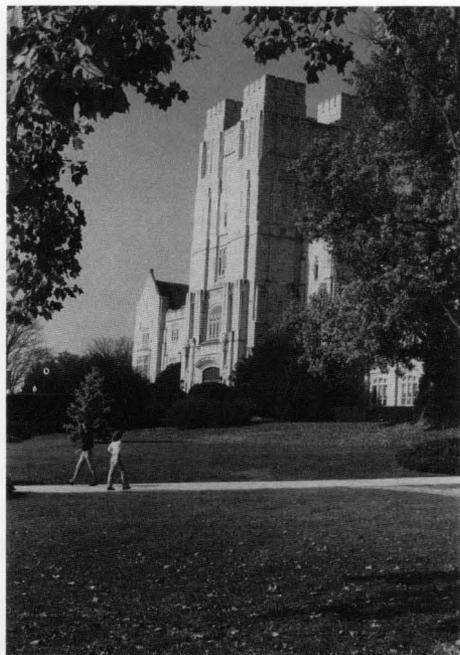
**Lembit U. Lilleleht** • *Ph.D., University of Illinois* • Fluid mechanics, heat transfer, multiphase systems, alternative energy

**John P. O'Connell** • *Ph.D., University of California, Berkeley* • Statistical thermodynamics with applications to physical and biological systems



*"Academic research should provide the opportunity for students to improve their methods of rational thought and inquiry with the advisor supplying insight and direction. The faculty here at UVA seem dedicated to allowing students the freedom to learn, but with guidance available when needed."*

*- Jamie Rudisill, B.S.ChE, North Carolina State University, Ph.D. candidate.*



Virginia



Tech

VIRGINIA POLYTECHNIC INSTITUTE  
AND STATE UNIVERSITY

**Graduate Study  
and Research  
at**

**VIRGINIA TECH . . .**

**SURFACE SCIENCE AND CATALYSIS**

heterogeneous catalysis • model catalyst systems • metal oxide surface chemistry • gas sensors • UHV surface analysis and high-pressure reaction studies

**BIOTECHNOLOGY AND BIOCHEMICAL  
PROCESS ENGINEERING**

affinity and immunoaffinity (monoclonal antibody) isolation of plasma proteins • transgenic expression and recovery of human plasma proteins in livestock • DNA amplification kinetics • in-situ biodegradation of toxic wastes

**SYSTEM AND COMPUTING  
TECHNOLOGY**

artificial intelligence • computer-aided design • process synthesis and integration

**HAZARDOUS WASTES**

in-situ treatment of ground water • textile dye waste minimization and treatments • microbubble flotation • enhanced biological treatments

**POLYMER SCIENCE AND ENGINEERING**

rheology • processing • morphology • synthesis • surface science • biopolymers • polymer suspensions • physical chemistry of polymer solutions • polyelectrolytes • polymer composites • fiber-reinforced composites

**COLLOID SCIENCE**

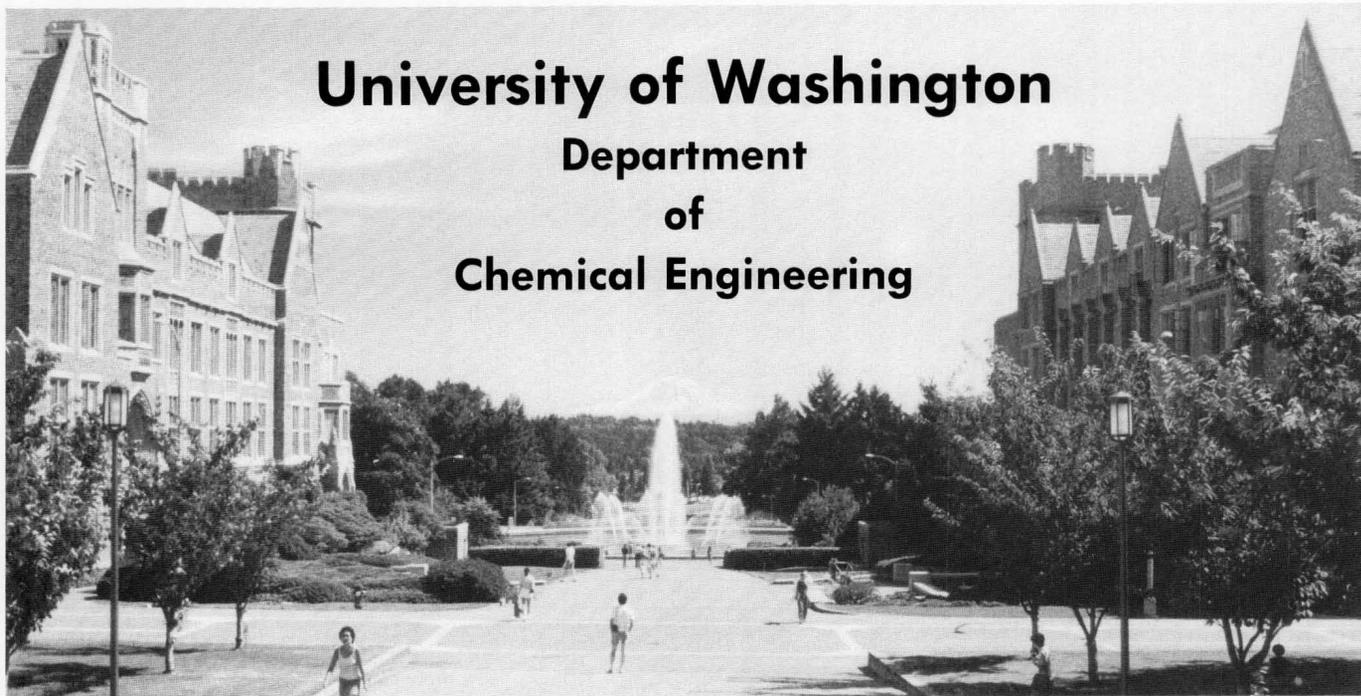
polymeric stabilization of suspensions • suspension rheology • synthesis of novel ceramic particles • physical chemistry of polymer adsorption at interfaces • associating polymers in solution



*For further information, contact the*

**Department of Chemical Engineering • Virginia Tech • 133 Randolph Hall  
Blacksburg, VA 24061**

**Telephone (703) 231-6631 Fax (703) 231-5022**



# University of Washington

## Department of Chemical Engineering

- Vigorous research program
- Excellent physical facilities
- Financial support for all full-time graduate students
- 65 graduate students from 30 universities and 20 states
- 15-20 students from foreign countries

Graduate students and faculty enjoy a fine *esprit de corps* in a stimulating and supportive research environment. Seattle, *The Emerald City*, provides outstanding cultural opportunities and unparalleled outdoor activities throughout the year. (Selected as the most livable city in the 1989 edition of *Places Rated Almanac*.)

### Inquiries welcome. Please contact:

Graduate Admissions  
 Department of Chemical Engineering, BF-10  
 University of Washington  
 Seattle, Washington 98195  
 Phone: (206) 543-2250  
 Fax: (206) 543-3778

### Chemical Engineering Faculty • Research Areas

- |  |  |
|--|--|
| <p>François Baneyx, Ph.D., Texas (Austin)</p> <p>John C. Berg, Ph.D., California (Berkeley)</p> <p>E. James Davis, Ph.D., Washington</p> <p>Bruce A. Finlayson, Ph.D., Minnesota</p> <p>William J. Heideger, Ph.D., Princeton</p> <p>Bradley R. Holt, Ph.D., Wisconsin</p> <p>Barbara Krieger-Brockett, Ph.D., Wayne State</p> <p>N. Lawrence Ricker, Ph.D., California (Berkeley)</p> <p>J. W. Rogers, Jr., Ph.D., Texas (Austin)</p> <p>Daniel T. Schwartz, Ph.D., California (Davis)</p> <p>James C. Seferis, Ph.D., Delaware</p> <p>Eric M. Stuve, Ph.D., Stanford</p> <p>Lewis E. Wedgewood, Ph.D., Wisconsin</p> | <ul style="list-style-type: none"> <li>• Biotechnology; Protein Technology; Biochemical Engineering</li> <li>• Interfacial Phenomena; Surface and Colloid Science</li> <li>• Colloid Science; Aerosol Chemistry and Physics; Electrokinetics</li> <li>• Mathematical Modeling</li> <li>• Mass Transfer</li> <li>• Process Design and Control</li> <li>• Reaction Engineering</li> <li>• Process Control and Optimization</li> <li>• Surface Science; Thin-Film Deposition</li> <li>• Electrochemical Engineering; Electrolytic Thin-Film Science</li> <li>• Polymeric Composites</li> <li>• Catalytic and Electrochemical Surface Science</li> <li>• Polymer Rheology</li> </ul> |
|--|--|

### Research Faculty

David G. Castner, Ph.D., California (Berkeley) • Biomaterials; Surface Science

### Adjunct and Joint Faculty Active in Department Research

- |   |   |
|---|---|
| <p>G. Graham Allan, Ph.D., D.Sc., Glasgow</p> <p>Albert L. Babb, Ph.D., Illinois</p> <p>Kermit L. Garlid, Ph.D., Minnesota</p> <p>Richard R. Gustafson, Ph.D., Washington</p> <p>Allan S. Hoffman, Sc.D., MIT</p> <p>Thomas A. Horbett, Ph.D., Washington</p> <p>William T. McKean, Ph.D., Washington</p> <p>Buddy D. Ratner, Ph.D., Brooklyn Polytechnic</p> <p>Gene L. Woodruff, Ph.D., MIT</p> | <ul style="list-style-type: none"> <li>• Fiber and Polymer Science</li> <li>• Biomedical Engineering; Hemodialysis</li> <li>• Nuclear Engineering; Radioactive Waste</li> <li>• Pulp and Paper</li> <li>• Biomaterials in Medicine and Biotechnology</li> <li>• Biomaterials; Peptide Drug Delivery</li> <li>• Pulp and Paper Science</li> <li>• Biomaterials; Polymers; Surface Characterization</li> <li>• Nuclear Engineering</li> </ul> |
|---|---|

# WASHINGTON STATE UNIVERSITY

## Chemical Engineering Department

Here at Washington State University, we are proud of our graduate program, and of our students. The program has been growing quickly in size and quality, but is still small and informal.

For a department of this size, the range of faculty research interests is very broad. Students choose research projects of in-

terest to them, then have the opportunity—and the responsibility—to make an individual contribution.

Through a combination of core courses and many electives, students can gain a thorough understanding of the basics of chemical engineering.

### FACULTY AND RESEARCH INTERESTS

**C. F. Ivory** (Ph.D., Princeton): bioseparations, including electrophoresis, electrochromatography and field flow fractionation.

**J. M. Lee** (Ph.D., University of Kentucky): plant tissue cultivation, genetic engineering, enzymatic hydrolysis, mixing

**K. C. Liddell** (Ph.D., Iowa State University): semiconductor electrochemistry, reactions on fractal surfaces, separations, radioactive waste management

**R. Mahalingam** (Ph.D., University of Newcastle-upon-Tyne): multiphase systems, physical and chemical separations, particulate phoretic phenomena, electronic materials and polymers, synfuels and environment

**J. N. Petersen** (Ph.D., Iowa State University): adaptive on-line optimization of biochemical processes, adaptive control, drying of food products

**J. C. Sheppard** (Ph.D., Washington University): radioactive wastes, actinide element chemistry, atmospheric chemistry, radiocarbon dating

**W. J. Thomson** (Ph.D. University of Idaho): kinetics of solid state reactions, sintering rates of ceramic and electronic material precursors, chemical reaction engineering

**B. J. Van Wie** (Ph.D., University of Oklahoma): kinetics of mammalian tissue cultivation, bio-reactor design, centrifugal blood cellular separations, development of biochemical sensors

**R. L. Zollars** (Ph.D., University of Colorado): multiphase reactor design, polymer reactor design, colloidal phenomena, chemical vapor deposition reactor design

### GRADUATE DEGREE PROGRAMS AT WSU

#### M.S. in Chemical Engineering

Twelve credits in graduate chemical engineering courses, nine credits in supporting courses, and a thesis are required.

#### Ph.D. in Chemical Engineering

Eighteen credits in graduate chemical engineering courses, sixteen credits in supporting courses, and a dissertation are required. Upon successful completion of the coursework and the Ph.D. preliminary examination, a student is admitted to candidacy for the degree. The dissertation must represent a significant original contribution to the research literature.

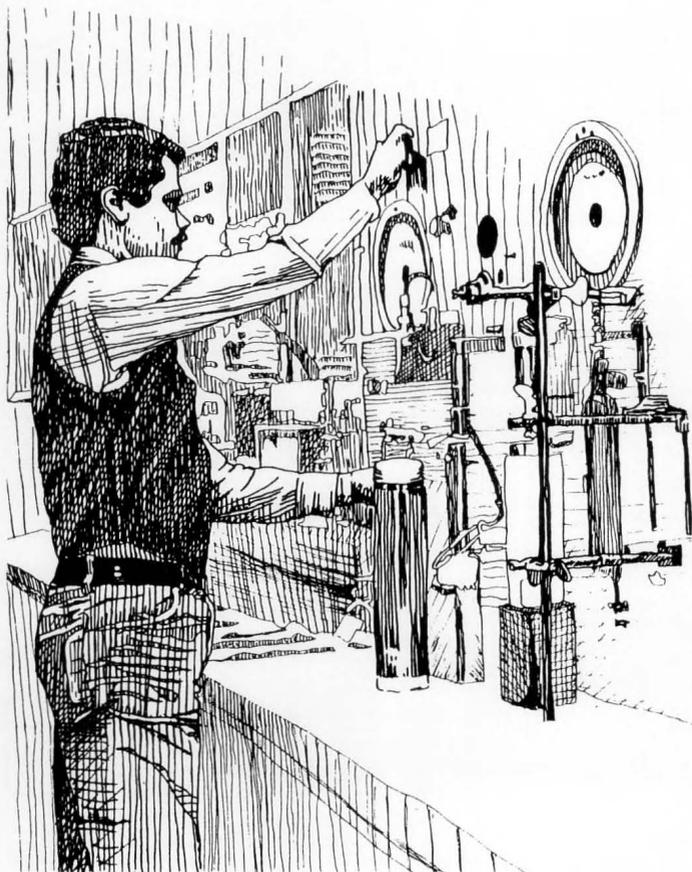
#### Conversion Program

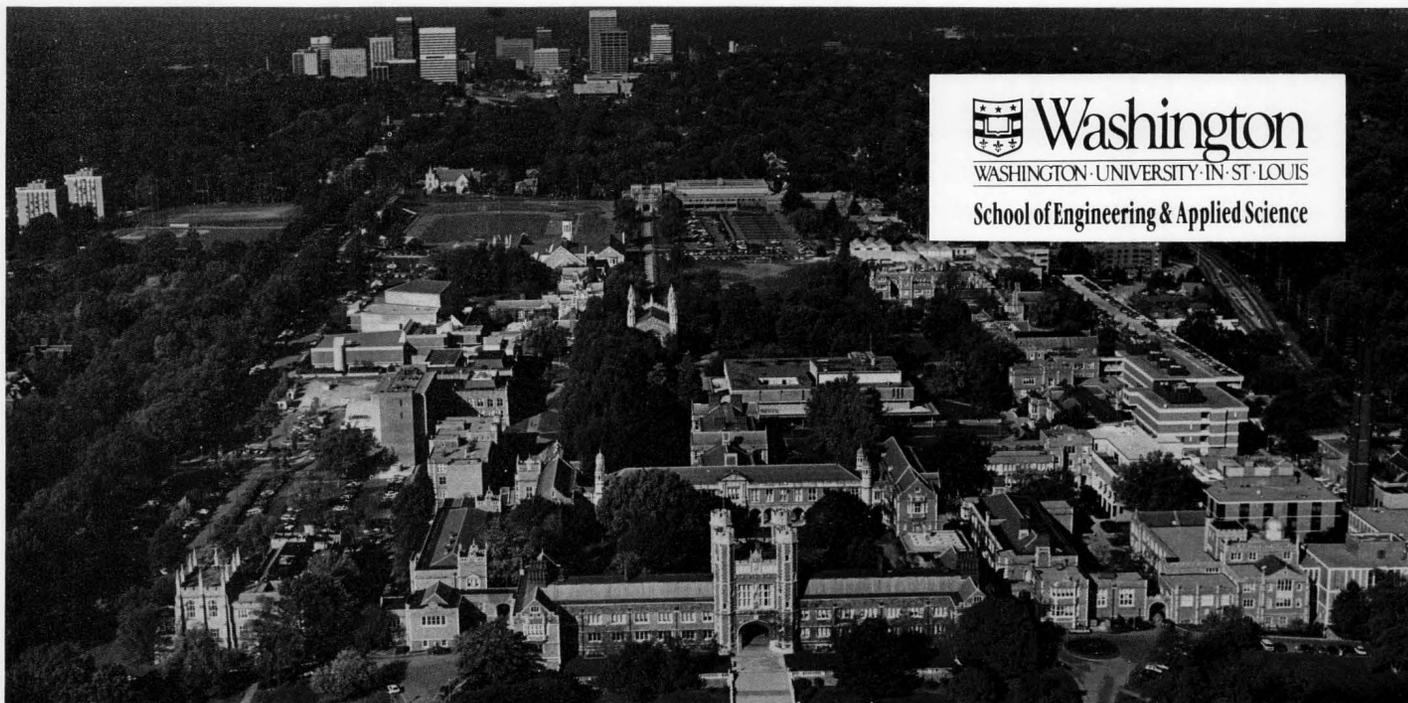
Students with B.S. degrees in the physical or life sciences may apply for admission to the conversion program. Normally a small number of undergraduate courses must be taken in addition to the regular requirements for the M.S. or Ph.D.

### FINANCIAL ASSISTANCE

Research or teaching assistantships, partial tuition waivers, and fellowships are available, and nearly all of our students receive financial assistance. Living costs are quite low.

**WANT TO APPLY? Contact: Dr. C. F. Ivory, Graduate Coordinator, Department of Chemical Engineering, Washington State University, Pullman, WA 99164-2710 509/335-4332 or 509/335-7716**





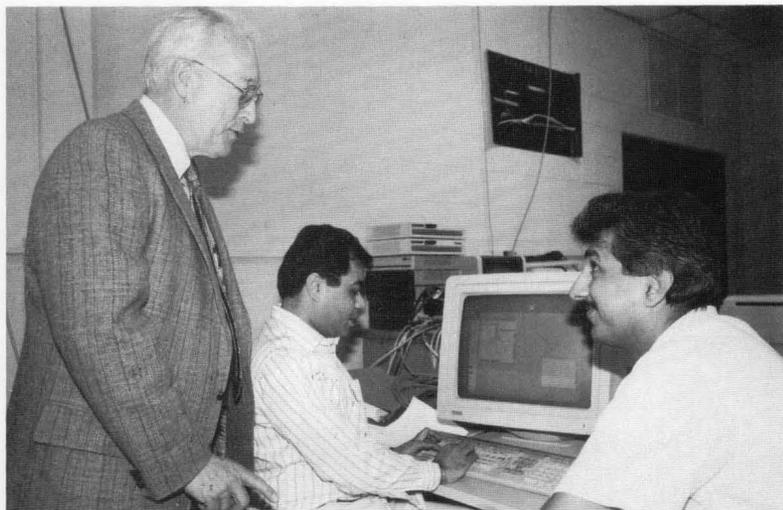

**Washington**  
 WASHINGTON · UNIVERSITY · IN · ST · LOUIS  
 School of Engineering & Applied Science

# GRADUATE STUDY IN **CHEMICAL ENGINEERING**

## MASTER'S AND DOCTORAL PROGRAMS

• Faculty and Research Areas •

- |                        |   |                           |   |
|------------------------|---|---------------------------|---|
| <b>M. P. Dudukovic</b> | Chemical Reaction Engineering                                       | <b>J. M. McKelvey</b>     | Polymer Science and Engineering                                 |
| <b>J. T. Gleaves</b>   | Heterogeneous Catalysis, Surface Science, Microstructured Materials | <b>R. L. Motard</b>       | Computer Aided Process Engineering, Knowledge-Based Systems     |
| <b>B. Joseph</b>       | Process Control, Process Optimization, Expert Systems               | <b>P. A. Ramachandran</b> | Chemical Reaction Engineering                                   |
| <b>J. L. Kardos</b>    | Composite Materials and Polymer Engineering                         | <b>R. E. Sparks</b>       | Biomedical Engineering, Microencapsulation, Transport Phenomena |
| <b>B. Khomami</b>      | Rheology, Polymer and Composite Materials Processing                | <b>C. Thies</b>           | Biochemical Engineering, Microencapsulation                     |
|                        |   | <b>M. Underwood</b>       | Unit Operations, Process Safety, Polymer Processing             |



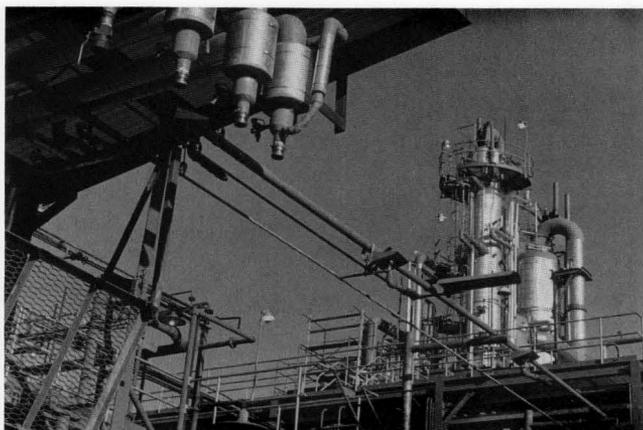
**For Information Contact**

**Graduate Admissions Committee**  
**Washington University**  
**Department of Chemical Engineering**  
 Campus Box 1198  
 One Brookings Drive  
 St. Louis, Missouri 63130-4899

*Washington University encourages and gives full consideration to application for admission and financial aid without respect to sex, race, handicap, color, creed or national origin.*

# West Virginia Institute of Technology and the West Virginia Graduate College

## *WANT THE BEST OF BOTH WORLDS?*



***Earn your Master's Degree in Control Systems Engineering  
in Wild, Wonderful West Virginia***

### **Tuition-free With a Stipend of \$1,000 a Month**

Earn while you learn in our 18-month graduate program that includes two summers of control work with one of our local industries, such as Union Carbide, DuPont, Rhone-Poulenc, Monsanto, FMC, Ashland Oil, or Ravenswood Aluminum.

Live, study, and work in the pristine natural environment of West Virginia, a land of rugged mountains, serene valleys, and enchanting rivers and streams. Classes are held in the Kanawha Valley, a bustling metropolitan area of 260,000—home of the state's capital city of Charleston and of a thriving chemical industry.

***This exciting opportunity is offered jointly  
by  
local industry,  
West Virginia Institute of Technology,  
and  
West Virginia Graduate College***

### *Schedule*

**Summer**

Industrial Internship, full-time work

**Fall**

3 cr hrs Advanced Differential Equations  
3 cr hrs Modeling Processes, ChE, ME, EE  
3 cr hrs Statistical Process Control  
3 cr hrs State-Space Control, Continuous

**Spring**

3 cr hrs Digital Control  
3 cr hrs Controlling Processes, ChE, ME, EE  
3 cr hrs Advanced Control  
3 cr hrs Project I, Planning Thesis Project

**Summer**

3 cr hrs Project II, Industrial Internship on project, full-time work

**Fall**

3 cr hrs Elective  
3 cr hrs Technical Communication  
3 cr hrs Project III, write up thesis, possible part-time work

***call or write***

Dr. Ed Crum  
Chemical Engineering Department  
West Virginia Institute of Technology  
Montgomery, WV 25316  
(304) 442-3163

— Or —

Dr. Bill Crockett  
School of Engineering and Science  
West Virginia Graduate College  
Institute, WV 25112  
(304) 766-2040



# West Virginia University

## Chemical Engineering

### *FACULTY*

---

**Richard C. Bailie** (*Iowa State University*)  
**Eugene V. Cilento**, Chairman (*University of Cincinnati*)  
**Dady B. Dadyburjor** (*University of Delaware*)  
**Rakesh K. Gupta** (*University of Delaware*)  
**Hisashi O. Kono** (*Kyushu University*)  
**Edwin L. Kugler** (*Johns Hopkins University*)  
**Joseph A. Shaeiwitz** (*Carnegie-Mellon University*)  
**Alfred H. Stiller** (*University of Cincinnati*)  
**Richard Turton** (*Oregon State University*)  
**Wallace B. Whiting** (*University of California, Berkeley*)  
**Ray Y. K. Yang** (*Princeton University*)  
**John W. Zondlo** (*Carnegie-Mellon University*)

### *TOPICS*

---

Catalysis and Reaction Engineering  
 Separation Processes  
 Surface and Colloid Phenomena  
 Phase Equilibria  
 Fluidization  
 Biomedical Engineering  
 Solution Chemistry  
 Transport Phenomena  
 Biochemical Engineering  
 Biological Separations  
 Polymer Rheology

## **M.S. and Ph.D. Programs**

*For Application Information, Write*  
 Professor Richard Turton • Graduate Admission Committee  
 Department of Chemical Engineering • P.O. Box 6101  
 West Virginia University  
 Morgantown, West Virginia 26506-6101

# Wisconsin

A tradition of excellence  
in Chemical Engineering



## Faculty Research Interests

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### **Kevin L. Bray**

High pressure solid-state chemistry, electronic properties of materials

### **Douglas C. Cameron**

Biotechnology, metabolic engineering

### **Thomas W. Chapman**

Electrochemical reaction engineering

### **Stuart L. Cooper (Chairman)**

Polymer physics, multiphase polymers, ionomers, biomaterials

### **Juan de Pablo**

Molecular thermodynamics, statistical mechanics

### **James A. Dumesic**

Kinetics and catalysis, surface chemistry

### **Charles G. Hill, Jr.**

Kinetics and catalysis, membrane separation processes, immobilized enzymes

### **Sangtae Kim**

Fluid mechanics, applied mathematics, parallel computing

### **Daniel J. Klingenberg**

Colloid science, transport phenomena

### **James A. Koutsky**

Polymer science, adhesives, composites

### **Thomas F. Kuech**

Semiconductor processing, solid-state and electronic materials, thin films

### **Stanley H. Langer**

Kinetics, catalysis, electrochemistry, chromatography, hydrometallurgy

### **E. N. Lightfoot, Jr.**

Mass transfer and separations processes, biochemical engineering

### **Regina M. Murphy**

Biomedical engineering, applied immunology, protein-protein interactions

### **W. Harmon Ray**

Process dynamics and control, reaction engineering, polymerization

### **Thatcher W. Root**

Surface chemistry, catalysis, solid-state NMR

### **Dale F. Rudd**

Process design and industrial development

### **Warren E. Stewart**

Reactor modeling, fractionation modeling, transport phenomena, applied mathematics

### **Ross E. Swaney**

Process design, synthesis, modeling, and optimization

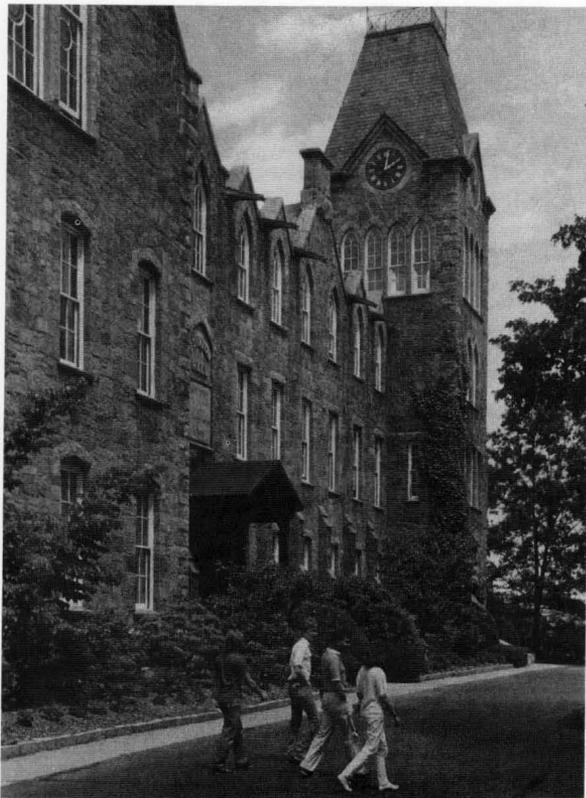
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For further information about  
graduate study in  
chemical engineering, write:

**The Graduate Committee**  
**Department of Chemical Engineering**  
**University of Wisconsin-Madison**  
**1415 Johnson Drive**  
**Madison, Wisconsin 53706-1691**

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# Graduate Studies in Chemical Engineering



Qualified students seeking M.S. and/or Ph.D. degrees will receive attractive fellowships or assistantships to pursue exciting fundamental and applied research.

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## Areas of Research:

### Advanced Materials

Carbon Filaments  
Inorganic Membranes  
Materials Processing in Space  
Metal Oxides  
Molecular Sieve Zeolites  
Superconductors

### Biochemical Engineering

Biopolymer Engineering  
Bioreactor Analysis  
Bioseparations

### Catalysis and Reaction Engineering

Adsorption and Transport in Porous Media  
Heterogeneous and Homogeneous Catalysis  
Zeolite Catalysis

## Faculty:

**W. M. Clark** • *Ph.D., Rice University*

**D. DiBiasio** • *Ph.D., Purdue University*

**A. G. Dixon** • *Ph.D., Edinburgh University*

**Y. H. Ma** • *Sc.D., Massachusetts Institute of Technology*

**J. W. Meader** • *S.M., Massachusetts Institute of Technology*

**W. R. Moser** • *Ph.D., Massachusetts Institute of Technology*

**J. E. Rollings** • *Ph.D., Purdue University*

**A. Sacco** • *Ph.D., Massachusetts Institute of Technology*

**R. W. Thompson** • *Ph.D., Iowa State University*

**A. H. Weiss** • *Ph.D., University of Pennsylvania*

---

## The Central New England Area:

WPI is situated on a 62-acre hilltop site in a residential area of Worcester, Massachusetts, New England's second largest city and a leading cultural, educational, and entertainment center. It is a one-hour drive from Boston and only two hours from the beaches of Cape Cod and the ski slopes and hiking trails of Vermont and New Hampshire.

## For further information, contact

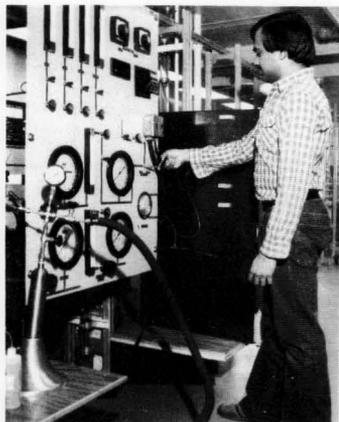
Graduate Coordinator  
Chemical Engineering Department  
100 Institute Road  
Worcester Polytechnic Institute  
Worcester, MA 01609-2280



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# WORCESTER POLYTECHNIC INSTITUTE

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Persons seeking admission, employment or access to programs of the University of Wyoming shall be considered without regard to race, color, national origin, sex, age, religion, political belief, handicap or veteran status.

# UNIVERSITY OF WYOMING

## Chemical Engineering

- C. Y. Cha** *solid waste utilization • microwave reactors • gas clean-up*  
**D. O. Cooney** *mass transfer • scrubbers • air and water pollution*  
**H. A. Deans** *enhanced oil recovery • carbon dioxide flooding*  
**R. D. Gunn** *coal drying • active carbon • mathematical modeling*  
**H. W. Haynes** *catalysis • reaction kinetics • synthetic fuels*  
**M. A. Matthews** *transport properties • thermodynamics*  
**C. R. McKee** *in-situ extraction of minerals*  
**M. Merrill** *applications of magnetic resonance imaging*  
**H. F. Silver** *coal liquefaction • desulfurization*  
**J. G. Speight** *coal chemistry*

We offer exciting opportunities for research in many processing areas, especially energy related technology development. In recent years we have developed clean coal, solid waste utilization, and advance gas clean-up technologies up to bench scale levels. Currently we are working with industry to construct and operate pilot units of these technologies. This will provide excellent opportunities for students to obtain hands-on experience on industrial projects. Also, research has been conducted in the areas of kinetics, catalysis, adsorption, extraction, computer modeling, coal processing, and enhanced oil recovery.

The Western Coal Consortium has been established by the Chemical Engineering Department with western coal producers and utilities. The Western Coal Consortium and Enhanced Oil Recovery Institute provide excellent financial aid packages to graduate students.

The University of Wyoming is located in Laramie, Wyoming at an elevation of 7200 feet. The town is surrounded by state and national parks which allow for beautiful year-round outdoor activities. The nearby Snowy Range mountains provide ideal sources of recreation for mountain and rock climbing, skiing, fishing, and hunting.

Graduates of any accredited chemical engineering program are eligible for admission, and the department offers both an M.S. and Ph.D. accredited program. Financial aid is available, and all recipients receive full fee waivers.

*For more information contact*

**Dr. Chang-Yul Cha, Head • Department of Chemical Engineering • University of Wyoming**  
P. O. Box 3295 • Laramie, WY 82071-3295

# YALE

# Department of Chemical Engineering



**Douglas D. Frey**, *Ph.D. Berkeley*  
**Gary L. Haller**, *Ph.D. Northwestern*  
**Csaba G. Horváth**, *Ph.D. Frankfurt*  
**James A. O'Brien**, *Ph.D. Pennsylvania*  
**Lisa D. Pfefferle**, *Ph.D. Pennsylvania*  
**Theodore W. Randolph**, *Ph.D. Berkeley*  
**Daniel E. Rosner**, *Ph.D. Princeton*  
**Robert S. Weber**, *Ph.D. Stanford*

***Adjunct Professors:***

- **Leslie S. Ettre**
- **John P. Marano**

***Lecturer:***

- **Joseph J. Levitzky**

---

Department of Chemical Engineering  
Yale University  
2159 Yale Station  
New Haven, Ct 06520  
Phone: (203) 432-2222  
FAX: (203) 432-7232

*Adsorption*  
*Aggregation, Clustering*  
*Biochemical Engineering*  
*Catalysis*  
*Chemical Reaction Engineering*  
*Chemical Vapor Deposition*  
*Chromatography*  
*Combustion*  
*Enzyme Technology*  
*Fine Particle Technology*  
*Heterogeneous Kinetics*  
*Interfacial Phenomena*  
*Molecular Beams*  
*Multiphase Transport Phenomena*  
*Separation Science and Technology*  
*Statistical Thermodynamics*  
*Supercritical Fluid Phenomena*

# BUCKNELL

BUCKNELL UNIVERSITY  
Department of  
Chemical Engineering

## MS PROGRAM

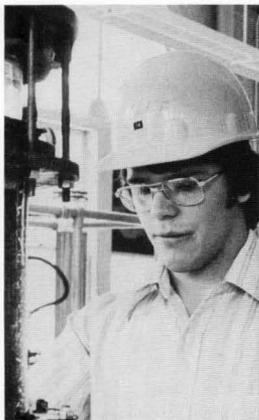
**W. E. KING, JR.,** Chair  
(PhD, University of Pennsylvania)  
*Modeling of biomedical systems*

**J. CSERNICA**  
(PhD, M.I.T.)  
*Materials science, polymer  
structures/property relations*

**M. E. HANYAK, JR.**  
(PhD, University of Pennsylvania)  
*Computer-aided design, thermodynamics,  
applied software engineering*

**F. W. KOKO, JR.**  
(PhD, Lehigh University)  
*Optimization, fluid mechanics, direct  
digital control*

**J. E. MANEVAL**  
(PhD, University of California, Davis)  
*Multiphase transport processes, ion exchange,  
nuclear magnetic resonance imaging*

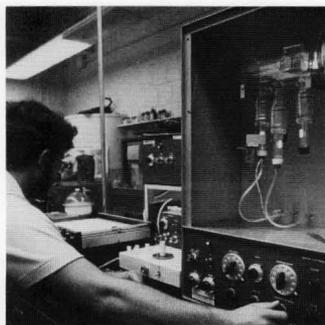


**J. M. POMMERSHEIM**  
(PhD, University of Pittsburgh)  
*Transport phenomena, mathematical  
modeling, cement hydration*

**M. J. PRINCE**  
(PhD, U. of California, Berkeley)  
*Biochemical engineering,  
interfacial phenomena*

**D. S. SCHUSTER**  
(PhD, West Virginia Univ.)  
*Fluidization, particulate systems,  
agglomerations*

**W. J. SNYDER**  
(PhD, Pennsylvania State U.)  
*Catalysis, polymerization,  
instrumentation*

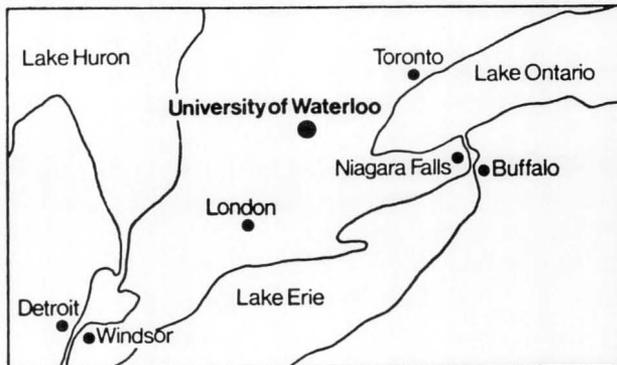


Bucknell is a small, private, highly selective university with strong programs in engineering, business, and the liberal arts. The Department is located in the newly renovated Charles A. Dana Engineering Building which provides ample facilities for both computational and experimental research. State-of-the-art Apollo workstations for both research and course work and modern laboratory equipment are readily available. Graduate students have a unique opportunity to work very closely with a faculty research advisor.

Lewisburg, located in the center of Pennsylvania, provides the attraction of a rural setting while conveniently located within 200 miles of New York, Philadelphia, Washington, D.C., and Pittsburgh.

For further information, write or phone  
**Dr. William E. King, Jr., Chair**  
Department of Chemical Engineering  
Bucknell University  
Lewisburg, PA 17837  
717-524-1114

## UNIVERSITY OF WATERLOO



**Canada's largest Chemical Engineering Department offers regular and co-operative M.A.Sc., Ph.D., and post-doctoral programs in:**

- Biochemical and Food Engineering
- Industrial Biotechnology
- Chemical Kinetics, Catalysis, and Reactor Design
- Environmental and Pollution Control
- Extractive and Process Metallurgy
- Polymer Science and Engineering
- Mathematical Analysis, Statistics, and Control
- Transport Phenomena, Multiphase Flow
- Enhanced Oil Recovery
- Electrochemical Processes, Solids, Handling

**Financial Aid:** RA: \$14,500/yr  
TA: \$5,000/yr (approximate)  
Scholarships

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The Associate Chairman (Graduate Studies)  
Department of Chemical Engineering  
University of Waterloo  
Waterloo, Ontario, Canada N2L 3G1  
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## Graduate Study in Chemical Engineering

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Richard A. Dobbins, Ph.D. (Princeton)  
Sture K. F. Karlsson, Ph.D. (Johns Hopkins)  
Joseph D. Kestin, D.Sc. (University of London)  
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Chemical Engineering Program  
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**David R. Miller** • Gas/Surface Interactions and Gas Dynamics  
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**K. Seshadri** • Reactive Gas Flows  
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 C. Steiner  
 G. Tardos  
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 Hydrodynamic Stability  
 Low Reynolds Number Hydrodynamics  
 Process Simulation and Control  
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M.Sc. and D.Eng. Programs

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- Adsorption Processes
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- Zeolites: Synthesis, Sorption, Diffusion
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**CSU** Cleveland State University

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- Carole A. Heath, Ph.D., RPI  
*PYI 1991-1996*
- Lee R. Lynd, D.E., Dartmouth  
*PYI 1990-1995*
- John Yin, Ph.D., Berkeley  
*Research Fellow: Max Planck Institute*

Contact: Director of Admissions • Biotechnology and Biochemical Engineering Program •  
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### RESEARCH AREAS

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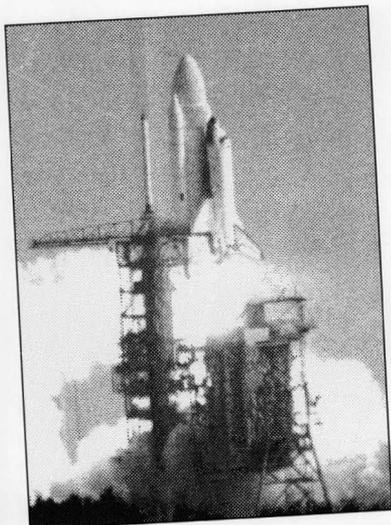
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- C. L. YAWS (Ph.D., University of Houston)

### RESEARCH AREAS

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- Fluidization, Incineration
- Transport Properties, Mass Transfer, Gas-Liquid Reactions
- Rheology of Drilling Fluids, Computer-Aided Design
- Thermodynamic Properties, Cost Engineering, Photovoltaics
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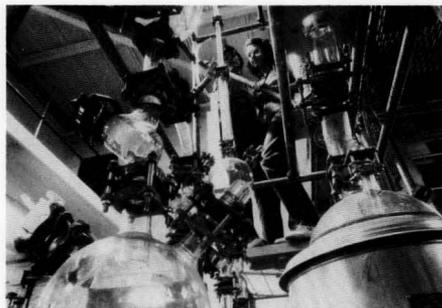
For information, write

Dr. H. K. Huckabay, Professor and Head  
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Louisiana Tech University  
Ruston, Louisiana 71272  
(318) 257-2483

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- Pulp and Paper Technology
- Chemical Reaction Engineering — Gas-Liquid, Gas-Solid, Three Phase
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- Biochemical Engineering — Continuous Culture
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**FOR FURTHER INFORMATION AND APPLICATION, WRITE**

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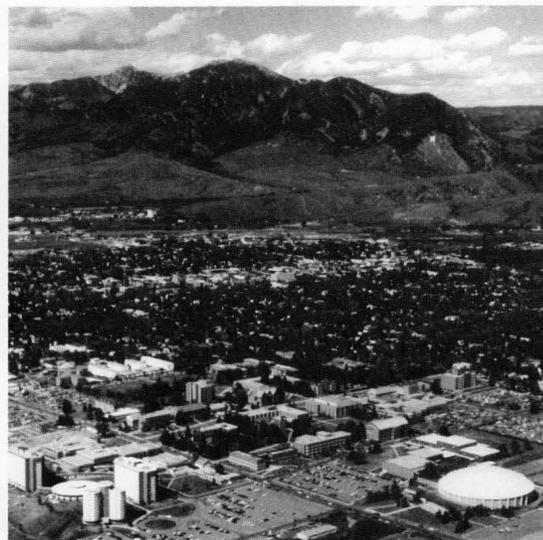
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**Information**

Dr. J. T. Sears, Head, Department of Chemical Engineering  
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# UNIVERSITY OF NEBRASKA



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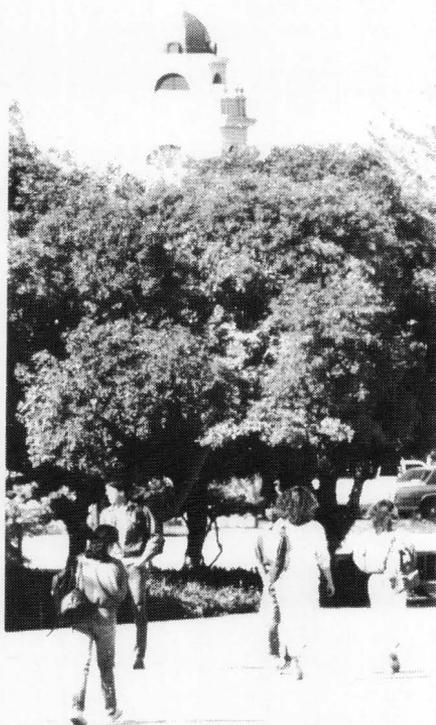


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For More Information Contact:

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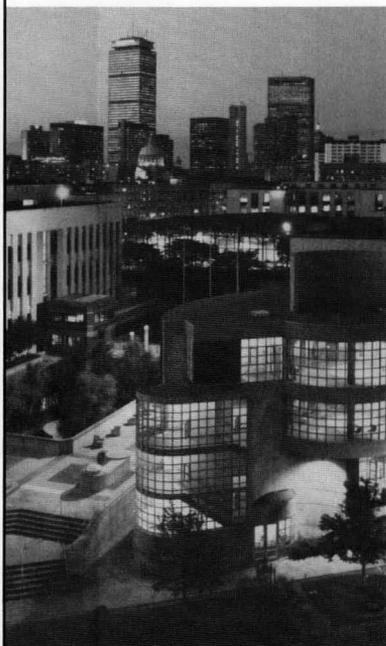
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## FOR INFORMATION WRITE:

Ralph A. Buonopane, Ph.D.  
Dept. of Chemical Engineering  
Northeastern University  
360 Huntington, 342 SN-CEE  
Boston, MA 02115

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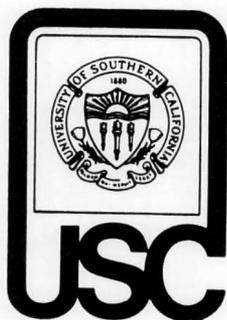
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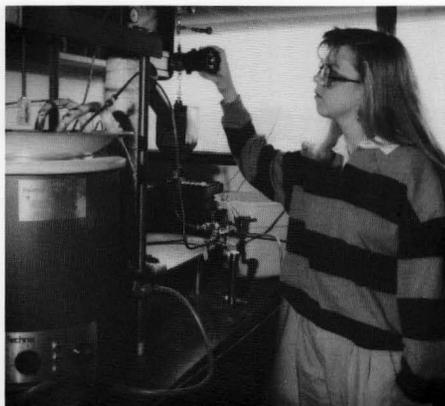
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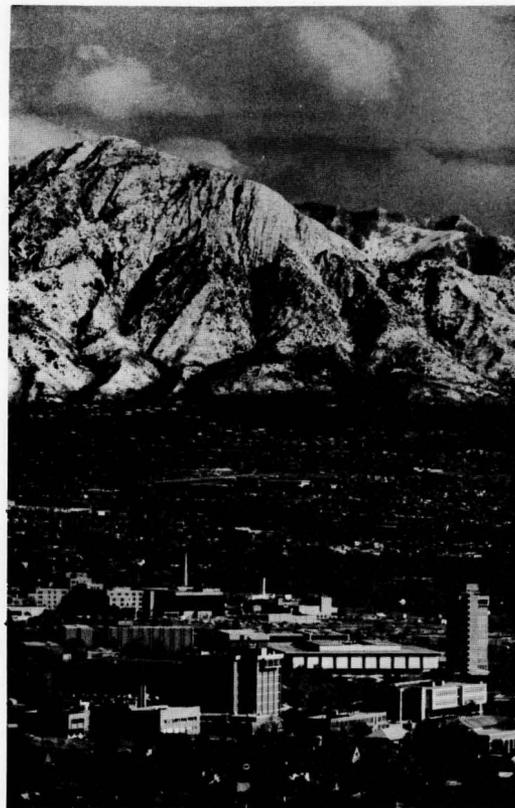
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