CEE chemical engineering education

VOLUME 26 NUMBER 4 FALL 1992

CHEMICAL ENGINEERING DIVISION OF AMERICAN SOCIETY FOR ENGINEERING EDUCATION

GRADUATE EDUCATION ISSUE

Featuring . . .

And also . . .

ACKNOWLEDGEMENT

DEPARTMENTAL SPONSORS

The following 153 departments contribute to the support of *CEE* with bulk subscriptions.

If your department is not a contributor, write to
CHEMICAL ENGINEERING EDUCATION,
c/o Chemical Engineering Department • University of Florida • Gainesville, FL 32611
for information on bulk subscriptions

University of Akron
University of Alabama
University of Alberta
University of Arizona
Arizona State University
University of Arkansas
Auburn University
Brigham Young University
University of British Columbia
Brown University
Bucknell University
University of Calgary
University of California, Berkeley
University of California, Davis
University of California, Irvine
University of California, Los Angeles
University of California, San Diego
University of California, Santa Barabara
California Institute of Technology
California State Poly Institute
Carnegie-Mellon University
Case Western Reserve University
University of Cincinnati
Clarkson College of Technology
Clemson University
Cleveland State University
University of Colorado
Colorado School of Mines
Colorado State University
Columbia University
University of Connecticut
Cooper Union
Cornell University
Dartmouth College
University of Dayton
University of Delaware
Drexel University
University of Edinburgh
University of Florida
Florida Institute of Technology
Florida State/Florida A&M University
Georgia Institute of Technology
University of Houston
Howard University
University of Idaho
University of Illinois, Chicago
University of Illinois, Urbana
Illinois Institute of Technology
Imperial College, London
University of Iowa
Iowa State University
Johns Hopkins University
University of Kansas
Kansas State University
University of Kentucky
Lafayette College
Lakehead University
Lamar University
Laval University
Lehigh University
Loughborough University
Louisiana State University
Louisiana Technical University
University of Louisville
Lowell University
Manhattan College
University of Maryland
University of Maryland, Baltimore County
University of Massachusetts
McGill University
McMaster University
McNeese State University
University of Michigan
Michigan State University
Michigan Technical University
University of Minnesota
University of Mississippi
Mississippi State University
University of Missouri, Columbia
University of Missouri, Rolla
Montana State University
University of Nebraska
University of New Hampshire
University of New Haven
New Jersey Institute of Technology
University of New Mexico
New Mexico State University
North Carolina A & T University
North Carolina State University
University of North Dakota
Northeastern University
Northwestern University
University of Notre Dame
Technical University of Nova Scotia
Ohio State University
Ohio University
University of Oklahoma
Oklahoma State University
Oregon State University
University of Ottawa
University of Pennsylvania
Pennsylvania State University
University of Pittsburgh
Polytechnic Institute of New York
Princeton University
Purdue University
Queen's University
Rensselaer Polytechnic Institute
University of Rhode Island
Rice University
University of Rochester
Rose-Hulman Institute of Technology
Rutgers, The State University
University of Saskatchewan
University of Sherbrooke
University of South Alabama
University of South Carolina
South Dakota School of Mines
University of South Florida
University of Southern California
University of Southwestern Louisiana
State University of New York, Buffalo
Stevens Institute of Technology
University of Syracuse
University of Tennessee
Tennessee Technological University
University of Texas
Texas A & M University
Texas Tech University
University of Toledo
Tri-State University
Tufts University
University of Tulsa
Tuskegee Institute
University of Utah
Vanderbilt University
Villanova University
University of Virginia
Virginia Polytechnic Institute
University of Washington
Washington State University
Washington University
University of Waterloo
Wayne State University
West Virginia College of Grad Studies
West Virginia Institute of Technology
West Virginia University
Widener University
University of Wisconsin
Worcester Polytechnic Institute
University of Wyoming
Yale University
Youngstown State University

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*

Chemical Engineering Division

Activities

1893 ASEE 1993
SHAPING OUR WORLD – CENTURY II

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 Illinois, 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:

Past Chairman •	Tim Anderson *(University of Florida)*
Chairman •	John C. Friedly *(University of Rochester)*
Chairman-Elect •	L. Davis Clements *(University of Nebraska)*
Secretary-Treasurer •	William L. Conger *(Virginia Polytechnic University)*
Directors •	Thomas R. Hanley *(University of Louisville)*
	Charles H. Barron *(Clemson University)*

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*

EDITORIAL AND BUSINESS ADDRESS:
Chemical Engineering Education
Department of Chemical Engineering
University of Florida
Gainesville, FL 32611
FAX 904-392-0861

Chemical Engineering Education

Volume 26 Number 4 Fall 1992

FEATURES

CLASS AND HOME PROBLEMS

RANDOM THOUGHTS

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. *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[1] 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[2] 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 relatively 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.

***Sangtae Kim** holds a Wisconsin Distinguished Professorship, with appointments in both chemical engineering and computer science at the University of Wisconsin. He received his BSc (1979) and MSc (1979) at Caltech and his PhD (1983) at Princeton. His research interests in computational microhydrodynamics encompass parallel computing solutions to problems in suspension rheology, colloidal hydrodynamics, and protein folding.*

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.

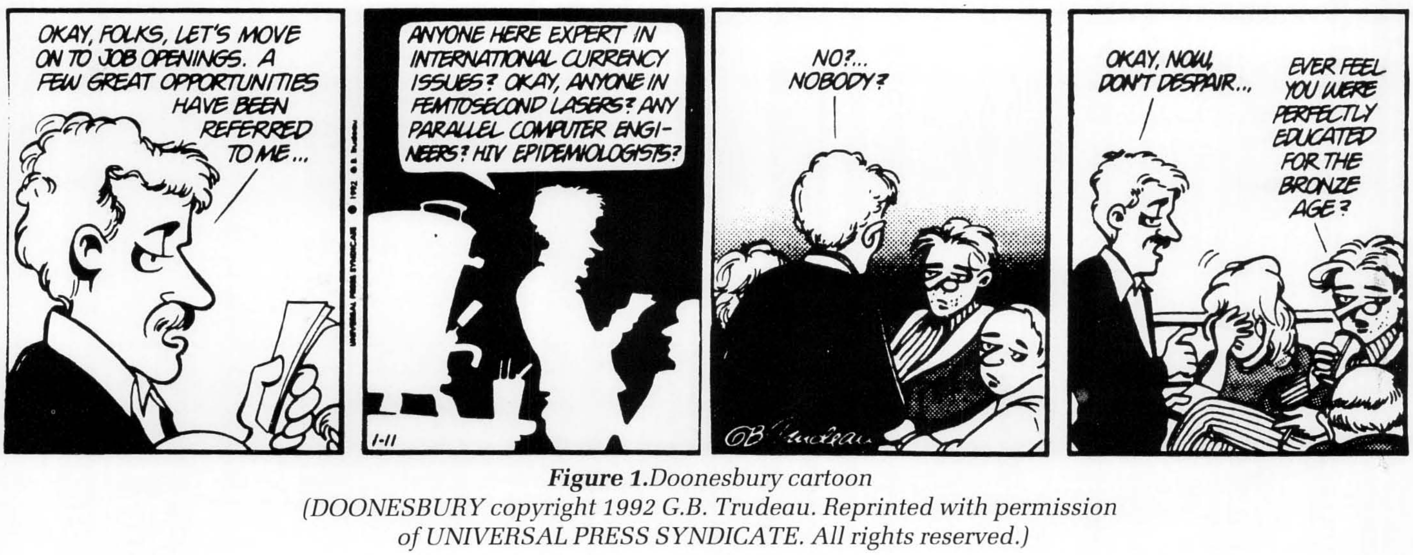


***Figure 1.** Doonesbury cartoon*
(DOONESBURY copyright 1992 G.B. Trudeau. Reprinted with permission of UNIVERSAL PRESS SYNDICATE. All rights reserved.)

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 . . .

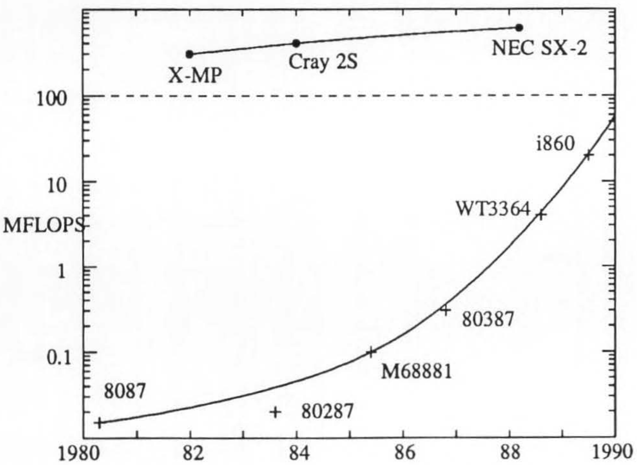


Figure 2. *Evolution of floating point performance during the 1980s. 1000 x 1000 LINPACK, from Dongarra.*[3]

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.[4] 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.[5]

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[6] 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,[7] 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[8] and subsequent visualization on Unix workstations with the ParaGraph software developed by Heath and coworkers.[9]

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.[10]

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.

REFERENCES

1. Amundson, N.R. (Committee Chairman), *Frontiers in Chemical Engineering Research Needs and Opportunities,* National Academy Press (1988)
2. Flynn, M.J., "Very High-Speed Computers," *Proc. IEEE,* **54**, 1901 (1966)
3. Dongarra, J.J., "Performance of Various Computers Using Standard Linear Equations Software," *Supercomputing Review,* **3**, 49 (1990)
4. Graubard, S.R. (Ed.), *DÆDALUS (J. Amer. Acad. Arts and Sci.),* Winter (1992)
5. Trew, A., and G. Wilson (Eds.), *Past, Present, Parallel: A Survey of Available Parallel Computing Systems,* Springer-Verlag (1991)
6. Bertsekas, D.P., and J.N. Tsitsiklis, *Parallel and Distributed Computation Numerical Methods,* Prentice Hall (1989)
7. Brawer, S., *Introduction to Parallel Programming,* Academic Press (1989)
8. Geist, G.A., M.T. Heath, B.W. Peyton, and P.H. Worley, "A Users' Guide to PICL: A Portable Instrumented Communication Library," *ORNL/TM,* **11616** March (1992)
9. Heath, M.T., and J.A. Etheridge, "ParaGraph: A Tool for Visualizing Performance of Parallel Programs," *ORNL/TM,* **11813** May (1991)
10. Kim, S., A.N. Beris, and J.F. Pekny, "Methodology of Parallel Computing," *AIChE Today Series,* AIChE (1990) ❐

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

Random Thoughts . . .

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

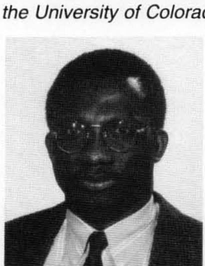
DOUGLAS J. COOPER, LUKE E.K. ACHENIE
University of Connecticut
Storrs, CT 06269-3139

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

Douglas J. Cooper *is Associate Professor of Chemical Engineering and Director of the Intelligent Process Systems Laboratory. He received a BS from the University of Massachusetts (1977), an MS from the University of Michigan (1978), and after three years of industrial experience with Chevron Research Company, a PhD from the University of Colorado (1985).*



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.*

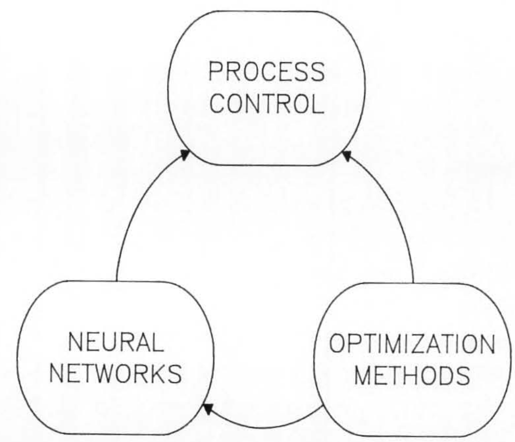


Figure 1. *Philosophical relationship guiding research program.*

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.

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-

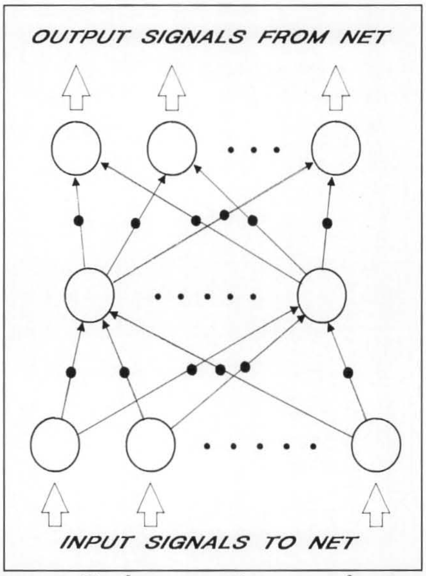


Figure 2. *Backpropagation neural network.*

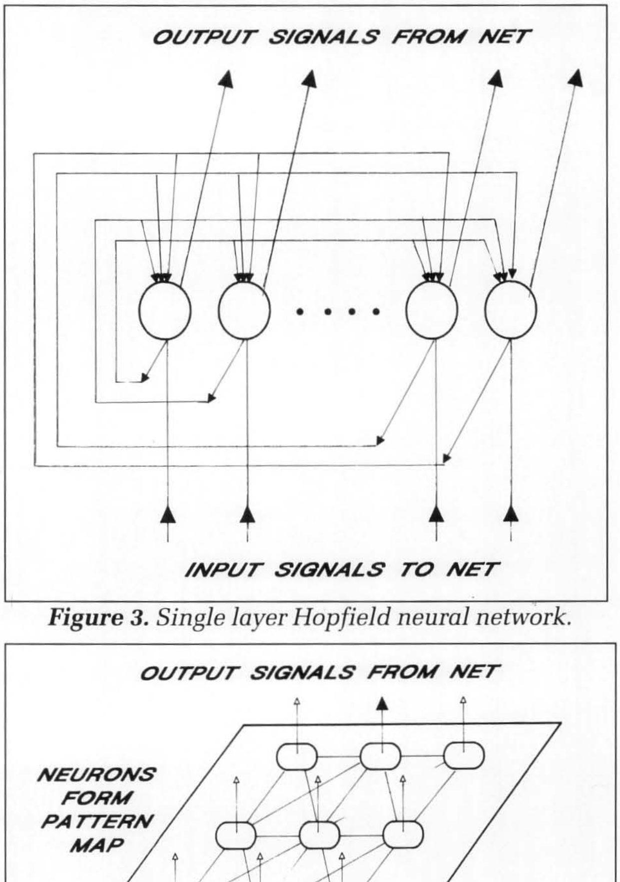


Figure 3. *Single layer Hopfield neural network.*

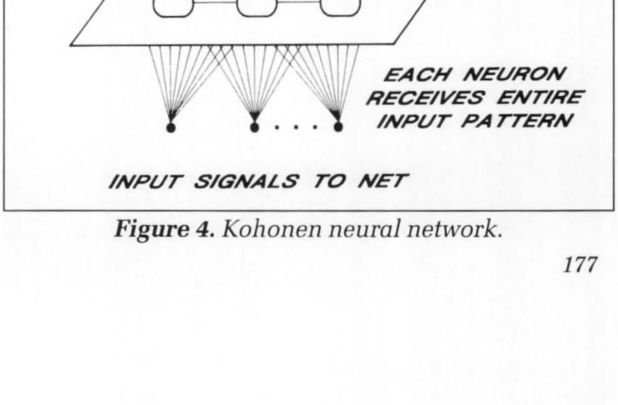


Figure 4. *Kohonen neural network.*

proaches[1] 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,[2] 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.[3]

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 behavior 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

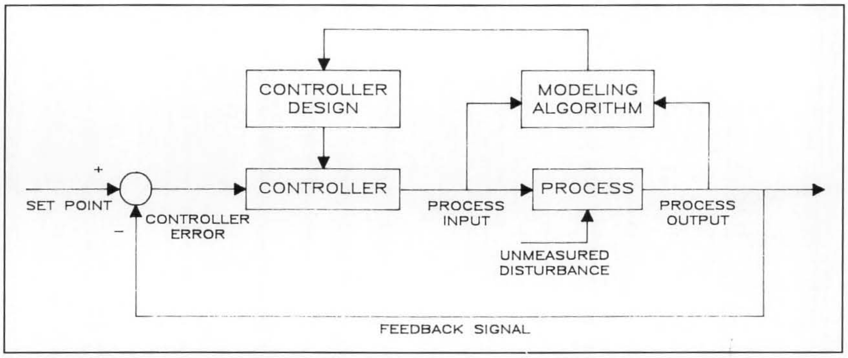


Figure 5. *Model-based adaptive process control architecture.*

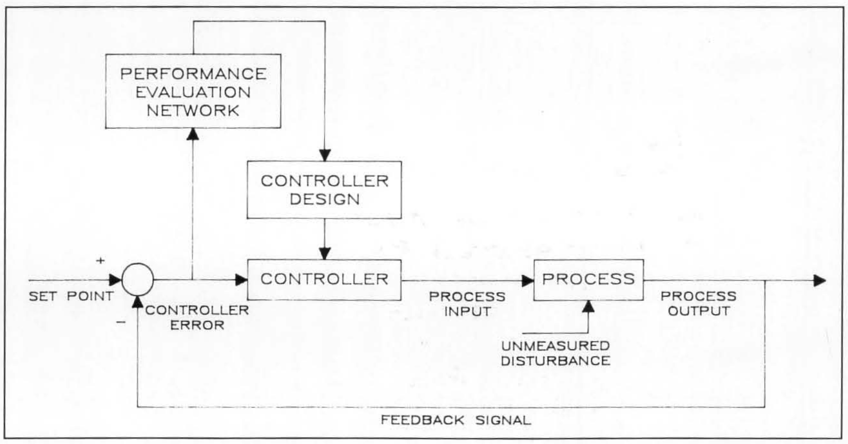


Figure 6. *Pattern-based performance feedback adaptive controller.*

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.

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.[2,4,5]

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.[6]

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.[7] 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

JOHN L. FALCONER
University of Colorado
Boulder, CO 80309-0424

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

$$A \Leftrightarrow B \qquad K_1 = 1.5 \tag{1}$$

$$A \Leftrightarrow C \qquad K_2 = 10 \tag{2}$$

Solution

A reasonable approach is to solve the two equilibrium equations simultaneously

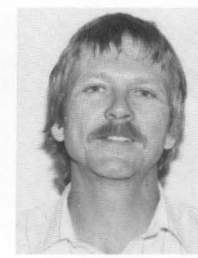
$$K_1 = \frac{x_B}{x_A} \qquad K_2 = \frac{x_C}{x_A}$$

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 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.

John L. Falconer *is professor of chemical engineering at the University of Colorado at Boulder, where he has been since 1975. He received his BS degree from the Johns Hopkins University and his PhD from Stanford University. He teaches courses in reactor design, thermodynamics, and catalysis. His research interests are in the areas of heterogeneous catalysis on supported metals and oxides, solid-catalyzed gas-solid reactions, photocatalysis, and catalytic membrane reactors.*



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[1-3]

- *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_2 clearly demonstrates this point. Consider the two reactions

	Equilibrium Constant at 500 K	
$CO + 2\,H_2 \Leftrightarrow CH_3OH$	5.3×10^{-3}	(3)
$2\,CO + 4\,H_2 \Leftrightarrow C_2H_5OH + H_2O$	32.8	(4)

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

$$x_{CO} = 0.50$$
$$x_{H_2} = 6 \times 10^{-3}$$
$$\boxed{x_{CH_3OH} = 4 \times 10^{-5}}$$
$$x_{C_2H_5OH} = 0.25$$
$$x_{H_2O} = 0.25$$

For this feed composition, the equilibrium calculation indicates that H_2 is almost completely consumed and the main products are ethanol and water. **Almost no** CH_3OH 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_2, and the undesired reactions are the formation of C_2H_5OH and hydrocarbons.

If only Reaction (3) is considered in the equilibrium calculation, however, then a reasonable yield of CH_3OH is predicted:

$$x_{CO} = 0.50$$
$$x_{H_2} = 0.36$$
$$\boxed{x_{CH_3OH} = 0.14}$$

In this case, only a fraction of the H_2 is consumed. Clearly this is the correct equilibrium calculation for the industrial process; **even though** C_2H_5OH **also forms**,[5,6] we do not consider Reaction (4) in the equilibrium calculation because Reaction (3) is so much faster. If we did, we would conclude that the measured methanol conversion is significantly higher than the equilibrium conversion. The formation of CH_3OH from CO and H_2 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).

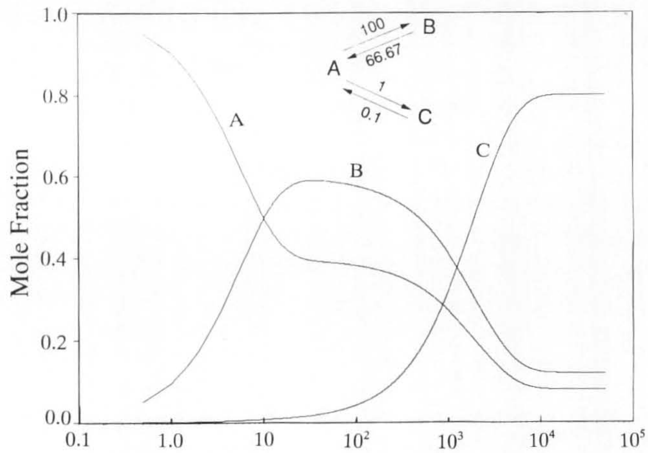


Figure 1. *Mole fractions of A,B,C versus reaction time for the parallel, reversible decomposition of A to form B and C. Rate constants in inverse minutes are indicated for first-order reactions.*

The interaction between catalysis and thermodynamics was discussed by Hamilton and Greenwald,[7] 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.[8] 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_3OH remains.[6] 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,[8] 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 CH_3OH is 0.14, not 4×10^{-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[7]

> *Of all the compounds that might theoretically form, it is well known that it is necessary to have thermodynamic information on only CO, H_2, and CH_3OH 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,[9] but they are formed in very low concentrations over the typical ZnO/Cr_2O_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.

REFERENCES

1. Holland, C.D., and R.G. Antony, *Fundamentals of Chemical Reaction Engineering,* Prentice Hall (1979)
2. Fogler, H.S., *Elements of Chemical Reaction Engineering,* 2nd ed. Prentice Hall (1992)
3. Smith, J.M., *Chemical Engineering Kinetics,* McGraw-Hill (1981)
4. O'Brien, J.A., REACT!, Version 2.0 program
5. Campbell, I.M., *Catalysis at Surfaces,* Chapman and Hall (1988)
6. Chinchen, G.C., P.J. Denny, J.R. Jennings, M.S. Spencer, and K.C. Waugh, *Appl. Catal.,* **36**, 1 (1988)
7. Hamilton, B.K., and M.J. Greenwald, *J. Chem. Ed.,* **51**, 732 (1974)
8. Satterfield, C.N., *Heterogeneous Catalysis,* McGraw-Hill (1980)
9. Klier, K., *Adv. in Catal.,* **31**, 243 (1982) ❒

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 immediately 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 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

L. K. DORAISWAMY
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,[1] was perhaps the first book to attempt a coherent educational presentation of the principles of reactor design.

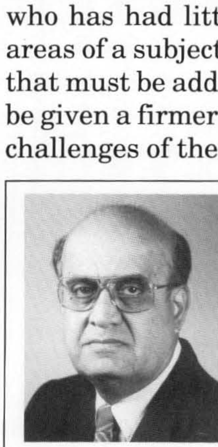
The subsequent development of chemical reaction engineering (CRE) was rapid, almost dramatic, in the 1960s and 1970s. The increasing use of sophisticated methods, so aptly and appropriately discussed by Aris,[2] provides a reflective backdrop to the continuing research in this area. The field has expanded 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 principles, 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.*

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.

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[3] 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[4] 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*,[5] 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*[6] 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[7]) 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,[8] 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[9] (also see Levenspiel[10] and Froment and Bischoff[11]). That is not so, however, with respect to unsteady state analysis (including multiplicity), for which some new mathematical tools have been developed.[12] 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.[13] 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[14] 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[4] 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_2, H_2S, SO_2, 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_2, 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 dixylylethane (DXE).[15] 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 intoPhase 1. From two excellent reviews on the subject,[16,17] 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,[18,19] Grignard reagent preparation by Hammerschmidt and Richarz,[20] and Kolbe-Schmitt reaction by Phadtare and Doraiswamy.[21]

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,[22] 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[23]). Another rewarding line of approach is the use of ultrasonics. The finding by Luche and Damiero[24] 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[25] 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 catalyzed 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[7] 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.[26] 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.

REFERENCES

1. Hougen, O.A., and K.M. Watson, *Chemical Process Principles,* Part 3, Kinetics and Catalysis, Wiley, NY (1947)
2. Aris, R., "Is Sophistication Really Necessary?" *Ind. Eng. Chem.,* **58**, 32(9) (1966)
3. Levenspiel, O., "Chemical Engineering's Grand Adventure," P.V. Danckwerts Memorial Lecture, *Chem. Eng. Sci.,* **43**, 1427 (1988)
4. Doraiswamy, L.K., and M.M. Sharma, *Heterogeneous Reactions: Analysis, Examples, and Reactor Design,* Vols. 1, 2, Wiley, NY (1984)
5. Bird, R.B., W.E. Stewart, and E.N. Lightfoot, *Transport Phenomena,* Wiley, NY (1960)
6. Rase, H.F., *Chemical Reactor Design for Process Plants,* Vols. 1,2, Wiley, NY (1977)
7. Doraiswamy, L.K., "Across Millenia: Some Thoughts on Ancient and Contemporary Science and Engineering," Hougen Lecture Series, Dept. of Chem. Engineering, University of Wisconsin, Madison, WI (1987)
8. Aris, R., and A. Varma, eds., *The Mathematical Understanding of Chemical Engineering Systems: Selected Papers of Neal R. Amundson,* Pergamon Press, NY (1980)
9. Aris, R., *The Mathematical Theory of Diffusion and Reaction in Permeable Catalysts,* Vols 1,2, Oxford Univ. Press, London, UK (1975) (The reference here is to Vol. 1)
10. Levenspiel, O., *Chemical Reaction Engineering,* Wiley, NY (1972)
11. Froment, G.F., and K.B. Bischoff, *Chemical Reactor Analysis and Design,* Wiley, NY (1990)
12. Luss, D., "Steady State Multiplicity Features of Chemically Reacting Systems," *Chem. Eng. Ed.,* **20**, 12 (1986)
13. Doraiswamy, L.K., "Chemical Reactions and Reactors: A Surface Science Approach," *Prog. Surf. Sci.,* **4**, Nos. 1-4, 1-277 (1991)
14. Gavriilidis, A., and A. Varma, "Optimum Catalyst Activity Profiles in Pellets: 9. Study of Ethylene Oxidation," *AIChE J.,* **38**, 291 (1992)
15. Sharma, M.M., "Separations Through Reaction," *J. Separ. Proc. Tech.,* **6**, 9 (1985)
16. Sharma, M.M., "The Fascinating Role of Microphases in Multiphase Reactions," *Proc. Indian Natnl. Sci. Acad.,* **57A**, No. 1, 99 (1991)
17. Mehra, A., "Intensification of Multiphase Reactions Through the Use of a Microphase: 1, Theoretical," *Chem. Eng. Sci.,* **43**, 899 (1988)
18. Gokhale, M.V., A.T. Naik, and L.K. Doraiswamy, "An Unusual Observation in the Disproportionation of Potassium Benzoate to Terephthalate," *Chem. Eng. Sci.,* **28**, 401 (1975)
19. Revankar, V.V.S., and L.K. Doraiswamy, "Kinetics of Thermal Conversion of Potassium Salts of Benzene (di- and tri-) Carboxylic Acids to Terephthalic Acid," *Ind. Eng. Chem. Res.,* **31**, 781 (1992)
20. Hammerschmidt, W.W., and W. Richarz, "Influence of Mass Transfer and Chemical Reaction on the Kinetics of Grignard Reagent-Formation for the Example of the Reaction of Bromocyclopentane with a Rotating Disk of Magnesium," *Ind. Eng. Chem. Res.,* **30**, 82 (1991)
21. Phadtare, P.G., and L.K. Doraiswamy, "Kolbe-Schmitt Carbonation of 2-naphthol," *Ind. Eng. Chem./Proc. Des. & Dev.,* **8**, 165 (1969)
22. Sharma, M.M., Lecture: "Selectivity Engineering," published by the Council of Scientific and Industrial Research, New Delhi, India (1990)
23. Baldyga, J., and J.R. Bourne, "A Fluid Mechanical Approach to Turbulent Mixing and Chemical Reaction," *Chem. Eng. Commun.,* **28**, 231 (1984)
24. Luche, J.L., and J.C. Damiero, "Ultrasonics in Organic Synthesis: 1, Effect on the Formation of Lithium Organometallic Reagents," *J. Am. Chem. Soc.,* **102**, 7926 (1980)
25. Hodge, P., and D.C. Sherrington, eds., *Polymer Supported Reactions in Organic Synthesis,* Wiley, NY (1980)
26. Brown, A.V., "Invention and Innovation—Who and How," *Chemtech* (Dec), 709 (1973) ❐

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

E.D. Sloan, R.M. Baldwin, D.J.T. Fiedler,
J.T. McKinnon, R.L. Miller
Colorado School of Mines
Golden, CO 80401

Dorothy 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 interviewers discourage participation in graduate work.

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 . . .

Dendy Sloan *has three degrees from Clemson University and did postdoctoral work at Rice University. He spent five years in industry at four DuPont locations. He has been at the Colorado School of Mines since 1976.*

Bob Baldwin *is a native of Iowa. He received his BS and MS from Iowa State University and his PhD from the Colorado School of Mines, all in chemical engineering. He joined the faculty in 1975 and is currently starting his third year as Department Head.*

D.J.T. Fiedler *has worked as administrative assistant in the chemical engineering department at the Colorado School of Mines for the last two years. Prior to that she spent three years at California Institute of Technology in the Environmental Engineering Department*

Tom McKinnon *has been an assistant professor at the Colorado School of Mines since August of 1991. He received his BS from Cornell in 1979 and his PhD from MIT in 1989. His research interests are in gas-phase chemical kinetics, combustion, hazardous waste destruction, and fullerene synthesis.*

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.*

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 midwestern 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 applicants 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 example, the national number of PhDs in science and engineering has been forecast by Atkinson[1] 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.

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.

The basis for our recruiting changes was obtained from a study by P.B. Brown[2] 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 admission 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.

REFERENCES

1. Atkinson, R.C., "Supply and Demand for Scientists and Engineers: A National Crisis in the Making," *Science,* **248**, 425 (1990)
2. Brown, P.B., "Cost Effectiveness of Common Recruitment Tools," Western Association of Graduate Schools Conference, Banff, Canada, March 4-6 (1989) ❒

AN INTRODUCTION TO THE FUNDAMENTALS OF BIO(MOLECULAR) ENGINEERING

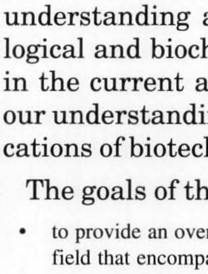
Bruce R. Locke
Florida State University, Florida A&M University
Tallahassee, FL 32316-2175

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 molecular 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.



***Bruce R. Locke** is an assistant chemical engineering professor at FAMU/FSU. He received his BE from Vanderbilt University in 1980, his MS from the University of Houston in 1982, and has four years of research experience at the Research Triangle Institute (North Carolina). He completed his PhD at North Carolina State in 1989. His research interests are in the dynamics of transport and reaction of biological macromolecules in multicomponent and multidomain composite systems.*

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.[1]

A recent work by Peacocke[2] reviews the literature on biochemical and biological organization that has arisen through the initial work of Hinshelwood in the 1940s and 1950s,[3] the work of A. Turing in the 1950s,[4] and the Brussels school of Prigogine in the 1960s to the present.[5] Peacocke overlooks the pioneering work of Rashevsky.[6,7] 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[8-11] and that the students' own fundamental knowledge of chemical reaction kinetics and transport phenomena can be used to describe, for example, slime mold aggregation,[12,13] cell cycle oscillations,[14] the formation of zebra and leopard spots,[12] the spread of a contagious disease,[12] the functioning of the immune system[15] and cardiac arrhythmia.[16] Important developments in the analysis of chemical reactions[10,11] have also aided the advancement of the compartmental analysis of biological systems.[17] 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 mechanochemical theory that links mechanical motion of molecular structures such as muscle and gel fibers to the chemical composition of the molecular structure[18,19] and solution are not fully addressed.

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

The details of molecular structure and function arise through introductions to molecular biology,[20,21] macromolecular science,[22-24] intermolecular interactions,[25] and recent studies on mechanochemical coupling.[18] 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.[26] Biomimicry for synthesizing new materials is also rapidly advancing.[27] 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 nonliving 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,[28] 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[5] 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.[29])

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.[30]

Mere descriptions of the hierarchal structure of taxonomy,[31] cells, subcellular organelles,[32] 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.[33-35] Concepts from mass transfer and fluid dynamics can be used to describe the structure of various sea creatures.[36] 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 organisms 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[37] or the transport of materials in and out of the cell[38] 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[39]).

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.[22-24,40] 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.[25] 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[41] 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[42]), antibody binding (avidin/biotin affinity chromatography[43]), cell surface interactions, and facilitated membrane transport (oxygen binding by hemoglobin and myoglobin[44]) can be described in detail. The quantitative description of these systems can be considered first from the thermodynamic approach[45-47] where binding equilibria are developed and second from the kinetic approach through Michaelis Menten type kinetics. Smoluchowski theory and Brownian motion[48] can be used to discuss diffusional limitations. In addition, recent work on the induced fit[49] 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[25] and in light of recent advances in active site directed binding.[41]

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,[50] modal analysis,[51] metabolic models,[52] cybernetic models[53] such as glycolysis, the regulation of protein synthesis, and the energetics of active transport in cell membranes[44]). 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.*[18] 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.[54,55] 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.[56] In addition, an introduction to population models[52,57,58] 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

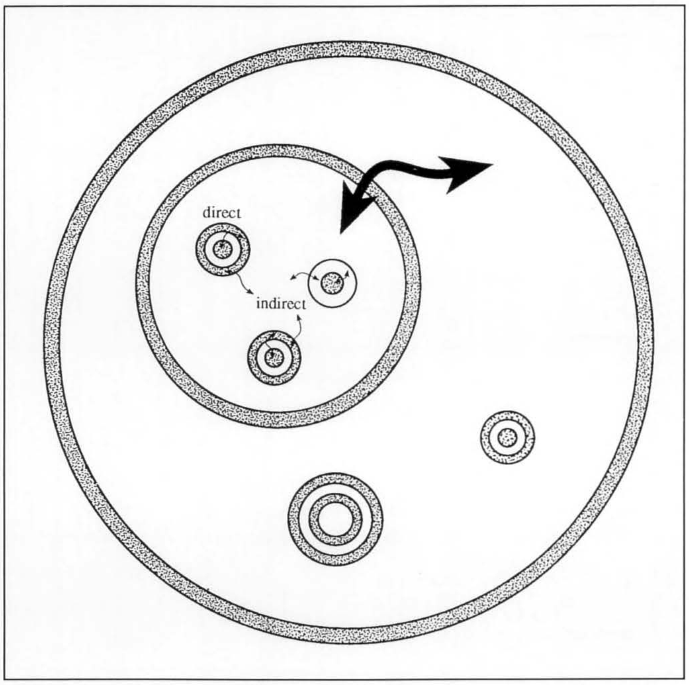


Figure 1. *Hierarchy of direct and indirect interactions*

science, and population balance approaches. This approach will lead to additional coursework to introduce molecular transport theories,[59] statistical mechanics, and even quantum mechanics for further study of bio(molecular) design.

ACKNOWEDGMENT

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 hierarchial levels of structure.

REFERENCES

1. Chen, C.-H.B., and D.S. Sigman, "Chemical Conversion of a DNA-Binding Protein into a Site-Specific Nuclease, *Science,* **237**, 1197 (1987)
2. Peacocke, A.R., *An Introduction to the Physical Chemistry of Biological Organization,* Oxford Science Publications, Clarendon Press, Oxford (1989)
3. Dean, A.C.R., and C. Hinshelwood, *Growth, Function and Regulation in Bacterial Cells,* Oxford at the Clarendon Press (1966)
4. Turing, A., "The Chemical Basis of Morphogenesis, *Proc. Roy. Soc. London,* **B237**, 5 (1952)
5. Nicolis G., and I. Prigogine, *Self-Organization in Nonequilibrium Systems,* Wiley-Interscience, New York (1977)
6. Rachevsky, N., "An Approach to the Mathematical Biophysics of Biological Self-Regulation and of the Cell Polarity, *Bull. Math. Biophy.,* **2**, 15 (1940)
7. Rachevsky, N., *Mathematical Biophysics,* University of Chicago Press, Chicago, IL (1948)
8. Othmer, H.G., and L.E. Scriven, "Interactions of Reaction and Diffusion in Open Systems," *I. & E.C. Fund.,* **8**, 302 (1969)
9. Gmitro, J.I., and L.E. Scriven, "A Physicochemical Basis for Pattern and Rhythm," in *Intracellular Transport,* K.B. Warren, Ed., Academic Press, New York (1966)
10. Wei, J., and C.D. Prater, "The Structure and Analysis of Complex Reaction Systems," Chap. 5 in *Advances in Catalysis,* Vol. 13, Academic Press, New York (1962)
11. Aris, R., "Compartmental Analysis and the Theory of Residence Time," in *Intracellular Transport,* K.B. Warren, Ed., Academic Press, New York (1966)
12. Murray, J.D., *Mathematical Biology,* Springer-Verlag, Berlin (1989)
13. Segel, L.A., *Modeling Dynamic Phenomena in Molecular and Cellular Biology,* Cambridge University Press, Cambridge (1984)
14. Norel, R., and Z. Agur, "A Model for the Adjustment of the Mitotic Clock by Cyclin and MPF Levels, *Science,* **251**, 1076 (1991)
15. Marchuk, G.I., *Mathematical Models in Immunology,* Optimization Software Inc., New York (1983)
16. Winfree, A.T., *When Time Breaks Down: The Three-Dimensional Dynamics of Electrochemical Waves and Cardiac Arrhythmias,* Princeton University Press (1987)
17. Anderson, D.H., *Compartmental Modeling and Tracer Kinetics,* Lecture Notes in Biomathematics, Vol. 50, Springer-Verlag (1983)
18. Murray, J.D., P.K. Maini, and R.T. Tranquillo, "Mechanochemical Models for Generating Biological Pattern and Form in Development," *Physics Reports,* **171**, 59 (1988)
19. Osada, Y., H. Okuzaki, and H. Hori, "A Polymer Gel with Electrically Driven Motility," *Nature,* **355**, 242 (1992)
20. Stryer, L., *Molecular Design of Life,* W. H. Freeman, New York (1989)
21. Primrose, S.B., *Molecular Biotechnology,* 2nd ed., Blackwell Scientific Publications, London (1991)
22. van Holde, K.E., *Physical Biochemistry*, 2nd ed., Prentice Hall, Inc., Englewood Cliffs, NJ (1985)
23. Tanford, C., *Physical Chemistry of Macromolecules,* John Wiley and Sons, Inc., New York (1966)
24. Cantor, C.R., and R. Schimmel, *Biophysical Chemistry,* Vols. 1-3, W.H. Freeman and Company, San Francisco, CA (1980)
25. Israelachvili, J., *Intermolecular and Surface Forces,* 2nd ed., Academic Press, London (1991)
26. De Castro, E.S., "Breathing Under Water," *Chemtech,* 682, Nov (1990)
27. Berman, A., *et al.,* "Intercalation of Sea Urchin Proteins in Calcite: Study of a Crystalline Composite Material, *Science,* **250**, 664 (1990)
28. Schrodinger, E., *What is Life? The Physical Aspect of the Living Cell and Mind and Matter,* Cambridge University Press (1944) (1966 reprint)
29. Kilmister, C.W., ed., *Schrodinger,* Cambridge University Press, Cambridge (1987)
30. Lasic, D. "Liposomes," *Amer. Sci.,* **80**, 20 (1992)
31. Margulis, L., and K. U. Schwartz, *An Illustrated Guide to the Phyla of Life on Earth,* 2nd ed., W.H. Freeman and Company, New York (1988)
32. de Duve, *A Guided Tour of the Living Cell,* Vols. 1 and 2, Scientific American Library (1984)
33. Vogel, S., "Life in Moving Fluids," *The Physical Biology of Flow,* Princeton University Press (1981)
34. Vogel, S., *Life's Devices: The Physical World of Animals and Plants,* Princeton University Press (1988)
35. McMahon, T.A., and J.T. Bonner, *On Size and Life,* Scuientific American Library (1983)
36. Patterson, M.R., "A Mass Transfer Explanation of Metabolic Scaling Relations in Some Aquatic Invertebrates and Algae," *Science,* **225**, 1421 (1992)

Continued on page 203.

A COLLOQUIUM SERIES IN CHEMICAL ENGINEERING

Costas Tsouris, Sotira Yiacoumi,
Cynthia S. Hirtzel
Syracuse University
Syracuse, NY 13244-1190

In describing a course on technical talks, Felder[1] points out the importance of communication skills for all practicing engineers. The significance of effective communication skills is also underlined by Hanzevack and McKean[2] 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 Department of Chemical Engineering and Materials Science at Syracuse University. Faculty and students are both concerned with the student's ability to communicate technical expertise.

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.

A seminar program called "**C**olloquium **S**eries in **C**hemical **E**ngineering and **M**aterials **S**cience" (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.[3] 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

***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)*

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.

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.

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 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.

REFERENCES

1. Felder, R.M., "A Course on Presenting Technical Talks," *Chem. Eng. Ed.,* **22**, 84 (1988)
2. Hanzevack, E.L., and R.A. McKean, "Teaching Effective Oral Presentations as a Part of the Senior Design Course," *Chem. Eng. Ed.,* **25**, 28 (1991)
3. Schulz, K.H., and G.G. Benge, "The Chemical Engineering Summer Seminar Series at Virginia Polytechnic Institute and State University," *Chem. Eng. Ed.,* **24**, 220 (1990) ❐

BIO(MOLECULAR) ENGINEERING

Continued from page 199.

37. Orci, L., J.-D. Vassalli, and A. Perrelet, "The Insulin Factory," *Sci. Am.,* Sept (1988)
38. Dautry-Varsat, A., and H.F. Lodish, "How Receptors Bring Proteins and Particles into Cells," *Sci. American,* **250**, 52 (1984)
39. Rothman, J.E., and L. Orci, "Molecular Dissection of the Secretory Pathway," *Nature,* **355**, 409 (1992)
40. Hiemenz, P.C. *Principles of Colloid and Surface Chemistry,* 2nd ed., Marcel Dekker, Inc., New York (1986)
41. Leckband, D.E., J.N. Israelachvili, F.-J. Schmitt, and W. Knoll, "Long Range Attraction and Molecular Rearrangements in Receptor-Ligand Interactions," *Science,* **225**, 1419 (1992)
42. Dressler, D., and H. Potter, *Discovering Enzymes,* Scientific American Library, W.H. Freeman (1991)
43. Wilchek, M., and E.A. Bayer, "The Avidin-Biotin Complex in Bioanalytical Applications," *Anal. Biochem.,* **171**, 1 (1988)
44. Segel, L.A., ed., *Mathematical Models in Molecular and Cellular Biology,* Cambridge University Press, Cambridge (1980)
45. Monod, J., J.-P. Changeux, and F. Jacob, "Allosteric Proteins and Cellular Control Systems, *J. Mol. Biol.,* **6** 306 (1963)
46. Monod, J., J. Wyman, and J.-P. Changeux, "On the Nature of Allosteric Transitions: A Plausible Model," *J. Mol. Biol.,* **12**, 88 (1965)
47. Wyman, J., and S.J. Gill, *Binding and Linkage: Functional Chemistry of Biological Macromolecules,* University Science Books (1990)
48. McCammon, J.A., and S.C. Harvey, *Dynamics of Proteins and Nucleic Acids,* Cambridge University Press (1987)
49. Rini, J.M., U. Schulze-Gahmen, and I.A. Wilson, "Structural Evidence for Induced Fit as a Mechanism for Antibody-Antigen Recognition," *Science,* **225**, 959 (1992)
50. Liao, J.C., and E.N. Lightfoot, "Lumping Analysis of Biochemical Reaction Systems with Time Scale Separation," *Biotech. and Bioeng.,* **31**, 869 (1988)
51. Palsson, B., H. Palsson, and E.N. Lightfoot, "Mathematical Modeling of Dynamics and Control in Metabolic Networks," *J. Theor. Biol.,* **113**, 231 (1985)
52. Shuler, M.L., and M.M. Domach, "Mathematical Models of the Growth of Individual Cells: Tools for Testing Biochemical Mechanisms," in *Foundations of Biochemical Engineering,* H.W. Blanch, E.T. Papoutsakis, and G. Staphanopoulos, eds., ACS Symp. Ser. 207, 93 (1983)
53. Straight, J.V., and D. Ramkrishna, "Complex Dynamics in Batch Cultures: Experiments and cybernetic Models," *Biotech. and Bioen.,* **37**, 895 (1991)
54. Bereiter-Hahn, J., O.R. Anderson, and W.-E Reif, eds, *Cytomechanics: The Mechanical Basis of Cell Form and Structure,* Springer-Verlag, Berlin (1987)
55. Derossi, D., K. Kajiwara, Y. Osada, and A. Yamauchi, *Polymer Gels: Fundamentals, Biomedical Applications,* Plenum Press, New York (1991)
56. Arce, P., and D. Ramkrishna, "Pattern Formation in Catalytic Reactors," *Latin Am. App. Res.,* in press (1992)
57. Ramkrishna, D., A.G. Fredrickson, and H.M. Tsuchiya, "Statistics and Dynamics of Procaryotic Cell Populations, *Math. Biosci.,* **1**, 327 (1967)
58. Metz, J.A.J., and O. Diekmann, *The Dynamics of Physiologically Structured Populations,* Lecture Notes in Biomathematics, Vol. 68, Springer-Verlag, Berlin (1986)
59. Peters, M.H., "An Introduction to Molecular Transport Phenomena," *Chem. Eng. Ed.,* **25**, 210 (1991) ❐

A Course on . . .

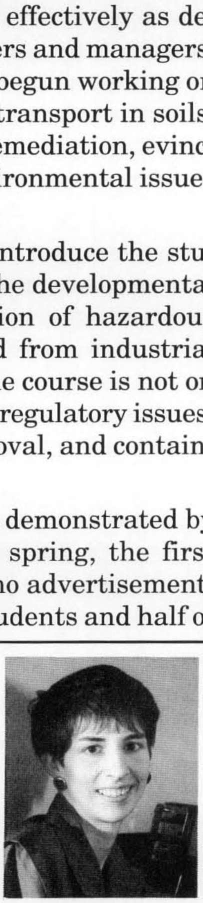
ENVIRONMENTAL REMEDIATION

Cynthia L. Stokes
University of Houston
Houston, TX 77204-4792

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 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.



***Cynthia Stokes** is an assistant professor in chemical engineering at the University of Houston. She received her BS from Michigan State University and her PhD from the University of Pennsylvania. She spent eighteen months as a post-doctoral fellow at the National Institutes of Health prior to arriving in Houston. Her major research focus has been in the area of cellular bioengineering.*

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.

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

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

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.

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[5] 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[6] 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[7] is used as a reference, and several other books serve as additional resources for the interested student.[8,9] 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.

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.

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*[10] 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[11] and several other recent reviews.[12-14]

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.[12-15]

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.[15] 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.[15-18] 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.[19]

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.[17,18] 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.[16] 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.[15] 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.[15,20] 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, vitrification, and pyrolysis. A major advantage of high temperature methods is the greater than 99% destruction of organic contaminants that is usually attainable.[15,20] 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.

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 . . .

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.[21,22] 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.[23,24] 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.[15]

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*.[15] 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.

REFERENCES

1. Hassan, S.S.M., *Analysis Using Atomic Absorption Spectrometry,* Ellis Horwood Limited, Chichester (1984)
2. Howe, I., D.H. Williams, and R.D. Bowen, *Mass Spectrometry Principles and Applications,* 2nd ed., McGraw-Hill, New York (1981)
3. Jennings, W., *Analytical Gas Chromatography,* Academic Press, Orlando, FL (1987)
4. Miller, J.M., *Chromatography: Concepts and Contrasts,* John Wiley and Sons, New York (1988)
5. Tchobanoglous, G., and E.D. Schroeder, *Water Quality: Characteristics-Modeling-Modification,* Addison-Wesley, Reading, MA (1985)
6. Hites, R.A., and W.L. Budde, *Env. Sci. Tech.,* **25**, 998 (1991)
7. Mercer, J.W., and R.M. Cohen, *J. Contam. Hydrol.,* **6**, 107 (1990)
8. Dullien, F.A.L., *Porous Media, Fluid Transport and Pore Structure,* Academic Press (1979)
9. Lake, L.W., *Enhanced Oil Recovery,* Prentice-Hall, New York (1989)
10. Bailey, J.E., and D.F. Ollis, *Biochemical Engineering Fundamentals,* McGraw-Hill, New York (1986)
11. U.S. Congress, Office of Technology Assessment, *Bioremediation for Marine Oil Spills—Background Paper* OTA-BP-O-70 (Washington, DC: U.S. Government Printing Office) (1991)
12. Nichols, A.B., *Water Env. Tech.,* p. 52, February (1992)
13. Saylor, G.S., *J. Haz. Mat.,* **28**, 13 (1991)
14. Shorthouse, B.T., *Remediation,* **1**, 31 (1990)
15. *Onsite Treatment: Hydrocarbon Contaminated Soils,* Environmental Solutions, Inc., Irvine, CA (1991)
16. Frick, T.D., R.L. Crawford, M. Martinson, T. Chresand, and G. Bateson, *Environmental Biotechnology,* G.S. Omenn, Ed., Plenum Press, New York, pp. 173-192 (1988)
17. Piotrowski, M.R., *Hydrocarbon Contam. Soils,* **1**, 433 (1991)
18. Piotrowski, M.R., and J.W. Carraway, "Full-Scale Bioremediation of Soil and Groundwater at a Superfund Site: A Progress Report," presented to HazMat South '91, Atlanta, GA (1991)
19. U.S. Environmental Protection Agency, Guide for Conducting Treatability Studies Under CERCLA: Aerobic Biodegradation Remedy Screening, Interim Guidance, EPA/540/2-91/013A (1991)
20. Freeman, H., *Innovative Thermal Hazardous Organic Waste Treatment Processes,* Noyes Publication, Park Ridge, NJ (1985)
21. Helling, R.K., and J.W. Tester, *Environ. Sci. Tech.,* **22**, 1319 (1988)
22. Thomason, T.B., and M. Modell, *Haz. Waste,* **1**, 453 (1984)
23. Perrich, J.R., *Activated Carbon Adsorption for Wastewater Treatment,* CRC Press, Boca Raton, FL (1981)
24. Voice, T.C., in *Standard Handbook of Hazardous Waste Treatment and Disposal,* H.M. Freeman, Ed., p. 6.3, McGraw-Hill, New York (1989) ❐

SOME THOUGHTS ON GRADUATE EDUCATION

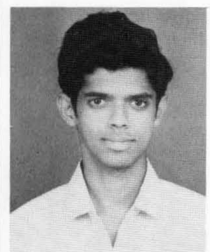
A Graduate Student's Perspective

RANGARAMANUJAM M. KANNAN
California Institute of Technology
Pasadena, CA 91125

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



__Rangaramanujam M. Kannan__ is a graduate student in chemical engineering at the California Institute of Technology. He received his BE (Hons.) from the Birla Institute of Technology and Science (India) and his MS degrees from Penn State and Caltech. His primary research interests are in polymer physics and fluid mechanics, with special emphasis on understanding polymer dynamics from a molecular level. His other interests include sports, Tamil music, and movies.

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 wisdom." 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[1] 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[2] 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[3] 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 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.)

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.

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.

REFERENCES

1. Duda, J.L., "Graduate Studies: The Middle Way," *Chem. Eng. Edn.*, **20**(4), 164 (1986)
2. Felder, R.M., "On Creating Creative Engineers," *Eng. Edn.*, p. 222, Jan (1987)
3. Felder, R.M., "A Generic Quiz: A Device to Stimulate Creativity and Higher-Level Thinking Skills," *Chem. Eng. Edn.*, **19**(4), 176 (1985) ❐

ChE **book review**

MODELING WITH DIFFERENTIAL EQUATIONS IN CHEMICAL ENGINEERING

by Stanley M. Walas

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

Reviewed by
M. Sami Selim
Colorado School of Mines

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 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.

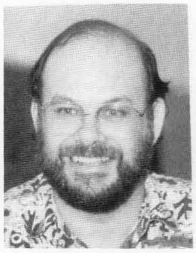
In summary, this is a highly recommendable textbook for senior and beginning graduate students, set apart by an easy style, a healthy amount of exercises, lots of references, and a wide coverage of topics. The author is to be commended for his excellent effort and contribution to the chemical engineering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

PATTERN FORMATION IN CONVECTIVE-DIFFUSIVE TRANSPORT WITH REACTION

Pedro Arce, Bruce R. Locke, Jorge Viñals
FAMU/FSU
Tallahassee, FL 32316-2175

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.[1,2]



__Pedro Arce__ received his ChE degree at Universidad Nacional del Litoral (Santa Fe, Argentina), and his MS and PhD degrees from Purdue University (1987, 1990). His main research interests are in applied computational mathematics, transport and reaction in multiphase systems, and molecular transport mechanics in material design.

__Bruce R. Locke__ received his BE from Vanderbilt University (1980) and has four years of research experience at the Research Triangle Institute (North Carolina). He completed his PhD at North Carolina State in 1989. His research interests are in the dynamics of transport and reaction of biological macromolecules in multicomponent and multidomain composite systems.

__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.

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 convectiv e and diffusive transport is considered. In the latter case the system is also kept not too far above the 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[3] 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.

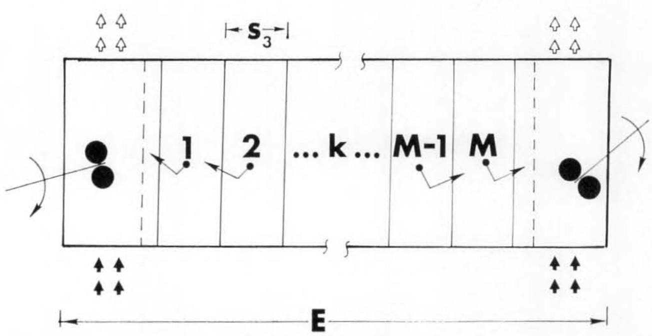


Figure 1. A single domain (which could itself be a subdomain of a larger domain), showing M subdivisions or layers such as the ones discussed in the text, and that corresponds to the model given in Eq. (1).

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[4,5] 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.[6] 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 direct and indirect interactions.[7] 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[8,13] 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^{th} layer is

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

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[9-11] and Parulekar and Ramkrishna.[12] This would give

$$V_0 \frac{dc_0}{dt} = c_{0f}F_0 - c_0F_0 + a\left[D_1\left(\frac{\partial c_1}{\partial x}\right)_{x=0^+} - u_1\left(\frac{V}{L}\right)_1 c_1(x=0^+)\right] \qquad (2)$$

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

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.[8-13] 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[6,7,14] and Ramkrishna and Arce[15-17] 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[6,7] 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-

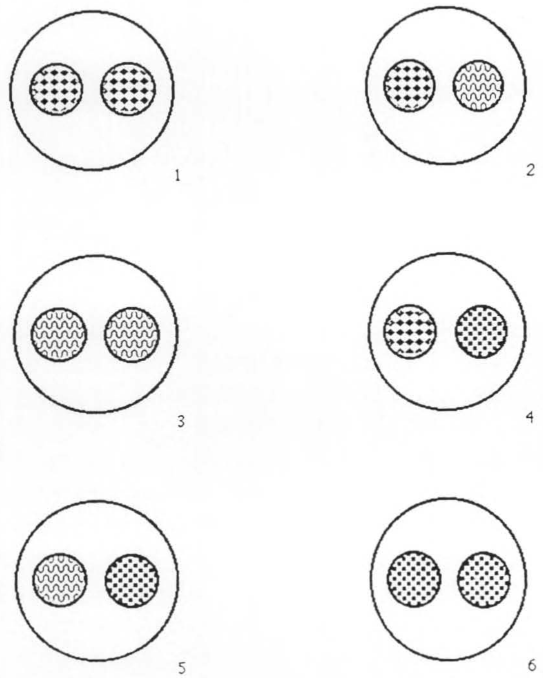


Figure 2. *Pattern formation in a well-mixed system showing two individual interacting catalytic particles or cells. Configurations 2, 4, and 5 clearly show the cells in two different steady states. Different steady states inside each cell are schematically depicted with different patterns.*

gularity theory and group-operator methods.[18] In addition, the investigation has been extended to catalytic packed-bed reactors[16] 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.[19] 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.[20] 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.[20,21] Generally, in isothermal systems, it is necessary for the chemical reactions to exhibit non-linear kinetics in order for temporal patterns to occur. Higgens[22] 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.[23]

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[4,24] and Turing.[5] Turing considered reaction and diffusion in a two-component and one-dimensional system.

Scriven and coworkers[25,26] have developed a general analysis of multicomponent reaction and diffusion in a single region coupled to other regions through indirect transfer expressions.

A large number of phenomena have subsequently been investigated from the perspective[20,27] 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.*,[28] 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[8,13] 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[29] 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.[30,31] 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 system 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[32] or on the electro-hydrodynamic instability in nematic liquid crystals.[33] 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.[34] 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

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

The quantity ε 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[35] 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 ε. 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 systems, 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.

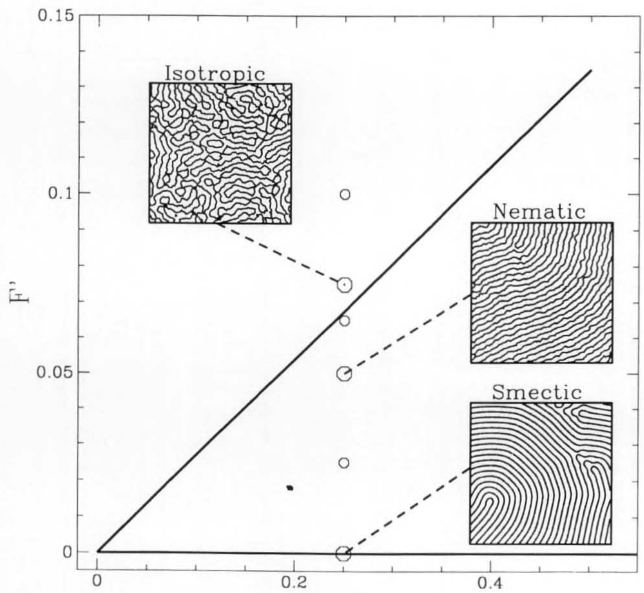


Figure 3. *Portions of typical configurations obtained as stationary solutions of Eq. (4). The configurations labeled isotropic, nematic, and smectic correspond to intensities of the fluctuations $F' = 0.075, 0.05$, and 0, respectively. In all these plots the lines drawn are the lines of $\psi(\vec{r})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

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.[36] 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.[37] 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."[38,39] 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[39,40] are focusing on the transient 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 acknowledge 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.

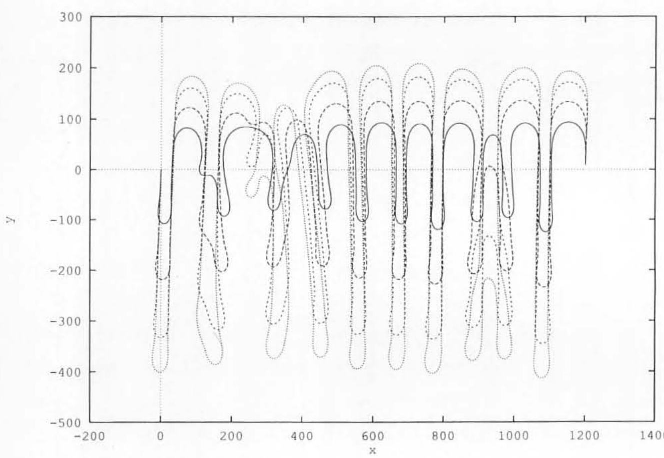


Figure 4. *Example of the temporal evolution of an interfacial pattern separating the solid and fluid phases during directional solidification. The lines shown are different times following the instability of a planar front.*

REFERENCES

1. Aris, R., *The Mathematical Theory of Diffusion and Reaction in Permeable Catalysts,* Vols. 1,2, Oxford University Press (1975)
2. Morbidelli, M., A. Varma, and R. Aris, "Reactor Steady State Multiplicity and Stability," in *Chemical Reactor and Reactor Engineering,* J. Carberry and A. Varma, Eds., M. Dekker, New York (1987)
3. Hill, J.M., *Solution of Differential Equations by Means of One Parameter Group,* Pitman, Boston, MA (1982)
4. Rachevsky, N., "An Approach to the Mathematical Biophysics of Biological Self-Regulation and of the Cell Polarity," *Bull. Math. Bioph.,* **2**, 15 (1940)
5. Turing, A.M., "The Chemical Basis of Morphogenesis," *Proc. Roy. Soc. B.,* **237**, 5 (1952)
6. Arce, P., and D. Ramkrishna, "Pattern Formation in Catalytic Reactors: The Role of Fluid Mixing," *AIChE J.,* **37**, 71 (1991)
7. Arce, P., and D. Ramkrishna, "Pattern Formation in Catalytic Reactors, Latin American Applied Research," (in press)
8. Locke, B.R., and P. Arce, "Applications of Self-Adjoint Operators to Electrophoretic Transport, Enzyme Reactions, and Microwave Heating Problems in Composite Media: I. General Formulation," *Chem. Eng. Sci.,* (in press)
9. Ramkrishna, D., and N.R. Amundson, *Linear Operator Methods in Chemical Engineering,* Prentice-Hall, Englewood Cliffs, NJ (1985)
10. Ramkrishna, D., and N.R. Amundson, "Stirred Pots, Tubular Reactors, and Self-Adjoint Operators, *Chem. Eng. Sci.,* **29**, 1353 (1974)
11. Ramkrishna, D., and N.R. Amundson, "Transport in Composite Materials: Reduction to a Self-Adjoint Formalism," *Chem. Eng. Sci.,* **29**, 1457 (1974)
12. Parulekar, S.J., and D. Ramkrishna, "Analysis of Axially Dispersed Systems with General Boundary Conditions: III. Solution for Unmixed and Well-Mixed Appended Sections," *Chem. Eng. Sci.,* **39**, 1599 (1984)
13. Locke, B.R., and P. Arce, "Applications of Self-Adjoint Operators to Electrophoretic Transport, Enzyme Reactions, and Microwave Heating Problems in Composite Media: II. Electrophoretic Transport in Layered Membranes," submitted to *Chem. Eng. Sci.* April (1992)
14. Arce, P., and D. Ramkrishna, "Self-Adjoint Operators of Transport in Interacting Solid-Fluid Systems," *Chem. Eng. Sci.,* **41**, 1539 (1986)
15. Ramkrishna, D., and P. Arce, "Can Pseudo-Homogeneous Reactor Models be Valid?" *Chem. Eng. Sci.,* **44**, 1949 (1989)
16. Ramkrishna, D., and P. Arce, "Some Further Observations on Heterogeneous Catalytic Reactor Models: Pattern Formation in Catalytic Reactors," *Chem. Eng. Sci.,* **46**, 3123 (1991)
17. Ramkrishna, D., and P. Arce, "Self-Adjoint Operators of Transport in Interacting Solid-Fluid Systems II," *Chem. Eng. Sci.,* **43**, 933 (1988)
18. Arce, P.E., "Fluid Mediated Interactions Among Particles in

a Catalytic Reactor," PhD Thesis, Purdue University (1990)
19. Arce, P., B.R. Locke, and B. Trigatti, "Transport and Reaction in Laminar Regime: A Boundary and Integral-Spectral Equation Approach," preprint (1992)
20. Peacocke, A.R., *An Introduction to the Physical Chemistry of Biological Organization,* Oxford (1989)
21. Nicolis, G., and I. Prigogine, *Self-Organization in Nonequilibrium Systems From Dissipative Structures to Order Through Fluctuations,* John Wiley and Sons, New York (1977)
22. Higgins, J., *I. & E.C.,* **59**, 19 (1967)
23. Norel, R., and Z. Agur, "A Model for the Adjustment of the Mitotic Clock by Cyclin and MPF Levels, *Science,* **251**, 1076 (1991)
24. Rachevsky, N., *Mathematical Biophysics,* University of Chicago Press, Chicago, IL (1948)
25. Gmitro, J.I., and L.E. Scriven, "A Physicochemical Basis for Pattern and Rhythm," in *Intracellular Transport,* K.B. Warren, ed., Academic Press (1966)
26. Othmer, H.G., and L.E. Scriven, "Interactions of Reaction and Diffusion in Open Systems," *I. & E. C. Fund.,* **8**, 302 (1969)
27. Britton, N.F., *Reaction-Diffusion Equations and Their Applications to Biology,* Academic Press, London (1986)
28. Martin, M.H., M.H.M. Goldsmith, and T.H. Goldsmith, "On Polar Auxin Transport in Plant Cells," *J. Math. Biol.,* **28**, 197 (1990)
29. Almirantis, Y., and S. Papageorgiou, "Cross-Diffusion Effects on Chemical and Biological Pattern Formation," *J. Theoret. Biol.,* **151**, 289 (1991)
30. Newell, A.C., in *Lectures in the Science of Complexity,* edited by D.L. Stein, Addison-Wesley, Redwood, p. 107 (1989)
31. Ahlers, G., in *Lectures in the Science of Complexity,* edited by D.L. Stein, Addison-Wesley, Redwood, p. 175 (1989)
32. Bodenschatz, E., J.R. de Bruyn, G. Ahlers, and D.S. Cannell, *Phys. Rev. Lett.,* **67**, 3078 (1991)
33. Rehberg, I., S. Rasenat, M. de la Torre, W. Schöpf, F. Hörner, G. Ahlers, and H.R. Brand, *Phys. Rev. Lett.,* **67**, 596 (1991)
34. Swift, J., and P.C. Hohenberg, *Phys. Rev. A.,* **15**, 319 (1977)
35. Elder, K.R., J. Viñals, and M. Grant, *Phys. Rev. Lett.,* **68**, 3024 (1992)
36. Pelce, P., *Dynamics of Curved Fronts,* Academic Press, New York (1988)
37. Mullins, W.W., and R.F. Sekerka, *J. Appl. Phys.,* **34**, 323 (1963)
38. Caroli, B., C. Caroli, and B. Roulet, *J. Physique,* **48**, 1423 (1987)
39. Viñals, J., and D. Jasnow, in *Computer Simulations in Condensed Matter Physics IV,* edited by D.P. Landau, *et al.,* Springer-Verlag, New York (1992)
40. Bennett, M.J., K. Tsiveriotis, and R.A. Brown, *Phys. Rev. B.,* **45**, 9562 (1992) ❐

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.

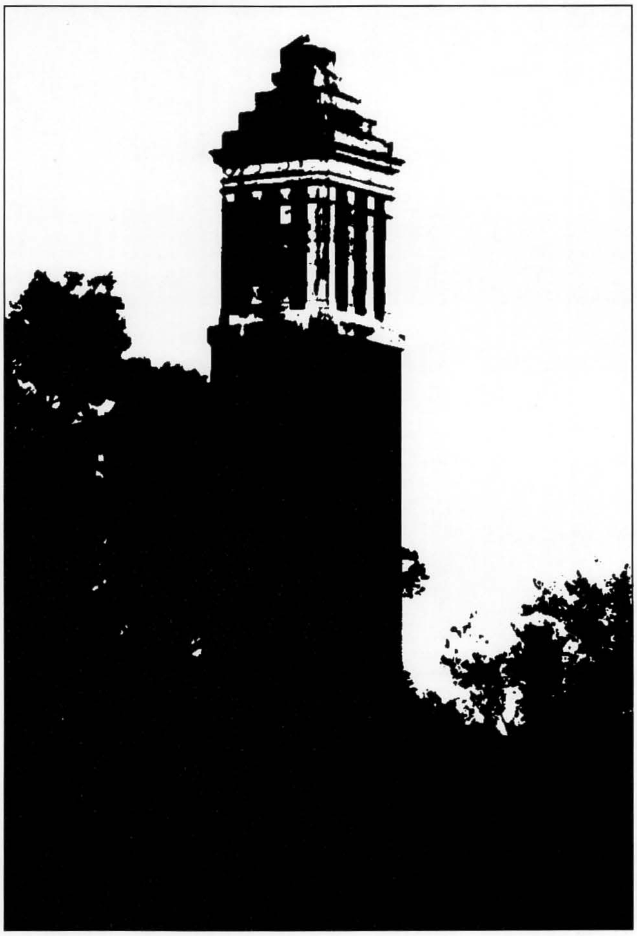
Such real-world implementations are important in process control research. When developments are restricted to simulated processes, the complete process character can be specified by the same researcher who is responsible for the control system developments. Real plants, on the other hand, have a process 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.

REFERENCES

1. Achenie, L.E., and L.T. Biegler, "A Superstructure Based Approach to Chemical Reactor Network Synthesis," *Comp. Chem. Eng.,* **14**, 23 (1990)
2. Cooper, D.J., L. Megan, and R.F. Hinde, Jr., "Comparing Two Neural Networks for Pattern Based Adaptive Process Control," *AIChE J.,* **38**, 41 (1992)
3. Vegeais, J.A., D.B. Garrison, and L.E.K. Achenie, "Parallel NCUBE Implementation of a Layered, Feed-Forward Neural Network," AIChE meeting, Los Angeles, CA; Nov. (1991)
4. Cooper, D.J., L. Megan, and R.F. Hinde, Jr., "Disturbance Pattern Classification and Neuro-Adaptive Control," *IEEE Cont. Sys.,* **12**, 42 (1992)
5. Hinde, R.F., Jr., and D.J. Cooper, "Adaptive Process Control Using Pattern-Based Performance Feedback," *J. of Proc. Cont.,* **1**, 228 (1991)
6. Cooper, D.J., and A.M. Lalonde, "Process Behavior Diagnostics and Adaptive Process Control," *Computers and Chem. Eng.,* **14**, 541 (1990)
7. Prett, D.M., C.E. Garcia, and B.L. Ramaker, *The Second Shell Process Control Workshop,* Butterworths (1990) ❐

CHEMICAL ENGINEERING PROGRAMS AT THE UNIVERSITY OF ALABAMA



The University of Alabama, located in the sunny South, offers excellent programs leading to M.S. and Ph.D. degrees in Chemical Engineering.

Our research emphasis areas are concentrated in environmental studies, reaction kinetics and catalysis, alternate fuels, and related processes. The faculty has extensive industrial experience, which gives a distinctive engineering flavor to our programs.

For further information, contact the Director of Graduate Studies, Department of Chemical Engineering, Box 870203, Tuscaloosa, AL 35487-0203; (205-348-6450).

FACULTY

G. C. April, Ph.D. (Louisiana State)
D. W. Arnold, Ph.D. (Purdue)
W. C. Clements, Jr., Ph.D. (Vanderbilt)
R. A. Griffin, Ph.D. (Utah State)
W. J. Hatcher, Jr., Ph.D. (Louisiana State)
I. A. Jefcoat, Ph.D. (Clemson)
A. M. Lane, Ph.D. (Massachusetts)
M. D. McKinley, Ph.D. (Florida)
L. Y. Sadler III, Ph.D. (Alabama)
V. N. Schrodt, Ph.D. (Pennsylvania State)

RESEARCH INTERESTS

Biomass Conversion, Modeling Transport Processes, Thermodynamics, Coal-Water Fuel Development, Process Dynamics and Control, Microcomputer Hardware, Catalysis, Chemical Reactor Design, Reaction Kinetics, Environmental, Synfuels, Alternate Chemical Feedstocks, Mass Transfer, Energy Conversion Processes, Ceramics, Rheology, Mineral Processing, Separations, Computer Applications, and Bioprocessing.

An equal employment/equal educational opportunity institution.

THE UNIVERSITY OF ARIZONA

TUCSON, AZ

The Chemical Engineering Department at the University of Arizona offers a wide range of research opportunities in all major areas of chemical engineering, and graduate courses are offered in most of the research areas listed below. The department offers a fully accredited undergraduate degree as well as MS and PhD graduate degrees. Strong interdisciplinary programs exist in bioprocessing and bioseparations, microcontamination in electronics manufacture, and environmental process modification. Financial support is available through fellowships, government and industrial grants and contracts, teaching and research assistantships.

THE FACULTY AND THEIR RESEARCH INTERESTS

ROBERT ARNOLD, Associate Professor[1] (Caltech)
Microbiological Hazardous Waste Treatment, Metals Speciation and Toxicity

JAMES BAYGENTS, Assistant Professor (Princeton)
Fluid Mechanics, Transport and Colloidal Phenomena, Bioseparations, Electrokinetics

MILAN BIER, Professor (Fordham)
Protein Separation, Electrophoresis, Membrane Transport

CURTIS W. BRYANT, Associate Professor[1] (Clemson)
Biological Wastewater Treatment, Industrial Waste Treatment

HERIBERTO CABEZAS, Assistant Professor (Florida)
Statistical Thermodynamics, Aqueous Two-Phase Extraction, Protein Separation

WILLIAM P. COSART, Associate Professor (Oregon State)
Heat Transfer in Biological Systems, Blood Processing

EDWARD FREEH, Adjunct Professor (Ohio State)
Process Control, Computer Applications

JOSEPH GROSS, Professor (Purdue)
Boundary Layer Theory, Pharmacokinetics, Microcirculation, Biorheology

ROBERTO GUZMAN, Assistant Professor (North Carolina State)
Protein Separation, Affinity Methods

BRUCE E. LOGAN, Associate Professor[1] (Berkeley)
Bioremediation, Biological Wastewater Treatment, Fixed Film Bioreactors

KIMBERLY OGDEN, Assistant Professor (Colorado)
Bioreactors, Bioremediation, Organics Removal from Soils

THOMAS W. PETERSON, Professor and Head (CalTech)
Aerosols, Hazardous Waste Incineration, Microcontamination

ALAN D. RANDOLPH, Professor (Iowa State)
Crystallization Processes, Nucleation, Particulate Processes

THOMAS R. REHM, Professor (Washington)
Mass Transfer, Process Instrumentation, Computer Aided Design

FARHANG SHADMAN, Professor (Berkeley)
Reaction Engineering, Kinetics, Catalysis, Reactive Membranes, Microcontamination

RAYMOND A. SIERKA, Professor[1] (Oklahoma)
Adsorption, Oxidation, Membranes, Solar Catalyzed Detox Reactions

JOST O. L. WENDT, Professor (Johns Hopkins)
Combustion-Generated Air Pollution, Incineration, Waste Management

DON H. WHITE, Professor Emeritus (Iowa State)
Polymers, Microbial and Enzymatic Processes

DAVID WOLF, Visiting Professor (Technion)
Fermentation, Mixing, Energy, Biomass Conversion

[1] *Joint appointment with Environmental Engineering Program, CEEM.*

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

For further information, write to

Chairman,
Graduate Study Committee
Department of Chemical Engineering
University of Arizona
Tucson, Arizona 85721

The University of Arizona is an equal opportunity educational institution/equal opportunity employer.
Women and minorities are encouraged to apply.

ARIZONA STATE UNIVERSITY

CHEMICAL, BIO, AND MATERIALS ENGINEERING

Graduate Research in a High Technology Environment

Chemical Engineering

Beckman, James R., Ph.D., U. of Arizona • Crystallization and Solar Cooling

Bellamy, Lynn, Ph.D., Tulane • Process Simulation

Berman, Neil S., Ph.D., U. of Texas, Austin • Fluid Dynamics and Air Pollution

Burrows, Veronica A., Ph.D., Princeton • Surface Science, Semiconductor Processing

Cale, Timothy S., Ph.D., U. of Houston • Catalysis, Semiconductor Processing

Garcia, Antonio A., Ph.D., U.C., Berkeley • Acid-Base Interactions, Biochemical Separation, Colloid Chemistry

Henry, Joseph D., Jr., Ph.D., U. of Michigan • Biochemical, Molecular Recognition, Surface and Colloid Phenomena

Kuester, James L., Ph.D., Texas A&M • Thermochemical Conversion, Complex Reaction Systems

Raupp, Gregory B., Ph.D., U. of Wisconsin • Semiconductor Materials Processing, Surface Science, Catalysis

Rivera, Daniel, Ph.D., Cal Tech • Process Control and Design

Sater, Vernon E., Ph.D., Illinois Institute of Tech • Heavy Metal Removal from Waste Water, Process Control

Torrest, Robert S., Ph.D., U. of Minnesota • Multiphase Flow, Filtration, Flow in Porous Media, Pollution Control

Zwiebel, Imre, Ph.D., Yale • Adsorption of Macromolecules, Biochemical Separations

Bioengineering

Dorson, William J., Ph.D., U. of Cincinnati • Physicochemical Phenomena, Transport Processes

Guilbeau, Eric J., Ph.D., Louisiana Tech • Biosensors, Physiological Systems, Biomaterials

Kipke, Daryl R., Ph.D., University of Michigan • Computation Neuroscience • Machine Vision, Speech Recognition, Robotics • Neural Networks

Pizziconi, Vincent B., Ph.D. Arizona State • Artificial Organs, Biomaterials, Bioseparations

Sweeney, James D., Ph.D., Case-Western Reserve • Rehab Engineering, Applied Neural Control

Towe, Bruce C., Ph.D., Penn State • Bioelectric Phenomena, Biosensors, Biomedical Imaging

Yamaguchi, Gary T., Ph.D., Stanford • Biomechanics, Rehab Engineering, Computer-Aided Surgery

Materials Science & Engineering

Dey, Sandwip K., Ph.D., NYSC of Ceramics, Alfred U. • Ceramics, Sol-Gel Processing

Hendrickson, Lester E., Ph.D., U. of Illinois • Fracture and Failure Analysis, Physical and Chemical Metallurgy

Jacobson, Dean L., Ph.D., UCLA • Thermionic Energy Conversion, High Temperature Materials

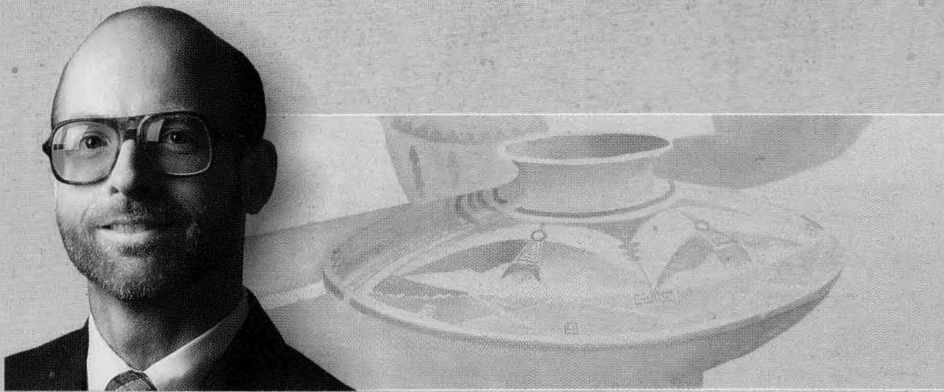
Krause, Stephen L., Ph.D., U. of Michigan • Ordered Polymers, Electronic Materials, Electron X-ray Diffraction, Electron Microscopy

Mayer, James, Ph.D., Purdue •Thin Film Processing • Ion Bean Modification of Materials

Stanley, James T., Ph.D., U. of Illinois • Phase Transformations, Corrosion

For more details regarding the graduate degree programs in the Department of Chemical, Bio, and Materials Engineering, please call (602) 965-3313 or (602) 965-3676, or write to: Dr. Eric Guilbeau, Chair of the Graduate Committee, Department of Chemical, Bio, and Materials Engineering, Arizona State University, Tempe, Arizona 85287-6006.

Leadership in engineering is an Arizona tradition.



Honeywell IAC, 1986

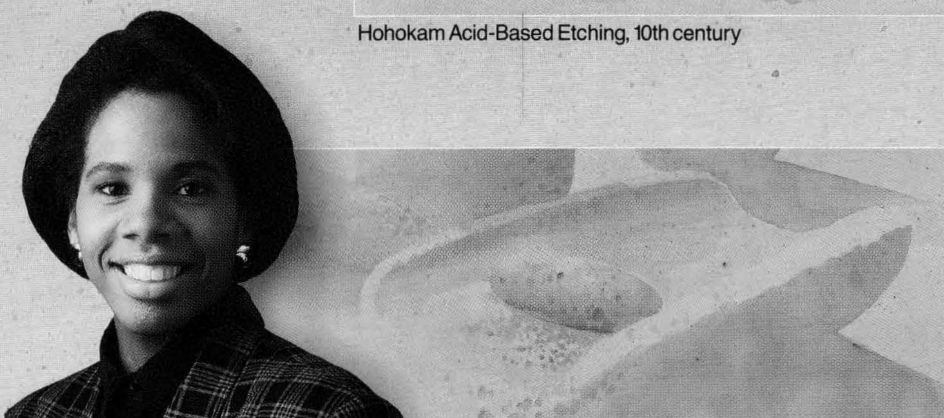
Hopi Pattern Mathematics, 6th century

As an Industrial Fellow at ASU, Mike Wall earned his master's degree while working for a major corporation. It's a unique opportunity, continuing a tradition of engineering excellence that began here hundreds of years ago.

Program sponsors include American Express, Honeywell, Intel, McDonnell Douglas Helicopter, Motorola and US WEST Small Business Services. They're helping engineers like Susan Ferreira invest in the future.

Hohokam Acid-Based Etching, 10th century

Motorola GEG, 1989



Intel, 1991

Sinaguan Metate Manufacturing, 13th century

In the next two years, Kim Solomon will be able to complete an advanced degree and earn over $55,000 in salaries, awards and benefits. She'll also participate in one of the nation's top leadership development programs for engineers.

Opportunities to earn a master's degree are available in computer science, or chemical, electrical, industrial or mechanical engineering. MBA opportunities are also available. U.S., Canadian or Mexican citizenship required.

Call **602-965-2276**
or write for more information. 1993 program applications are due by December 1, 1992 (early bird) or January 15, 1993 (final).

Industrial Fellows Program

ARIZONA STATE UNIVERSITY

A Part Of The ASU Corporate Leaders Program

College of Engineering and Applied Sciences
Tempe, Arizona 85287-7406
(602) 965-2276 FAX (602) 965-2267

Arizona State University vigorously pursues affirmative action and equal opportunity in its employment, activities, and programs.

THE UNIVERSITY OF CALIFORNIA AT BERKELEY . . .

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

FACULTY

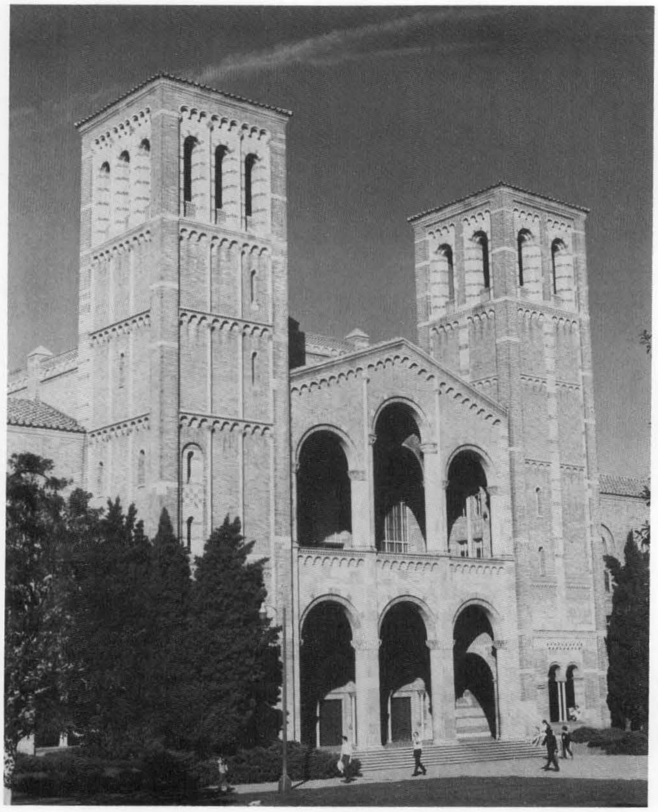
ALEXIS T. BELL
HARVEY W. BLANCH
ELTON J. CAIRNS
ARUP K. CHAKRABORTY
DOUGLAS S. CLARK
MORTON M. DENN (CHAIRMAN)
ALAN S. FOSS
SIMON L. GOREN
DAVID B. GRAVES
JAY D. KEASLING
C. JUDSON KING
SCOTT LYNN
SUSAN J. MULLER
JOHN S. NEWMAN
JOHN M. PRAUSNITZ
CLAYTON J. RADKE
JEFFREY A. REIMER
DAVID S. SOANE
DOROS N. THEODOROU

RESEARCH INTERESTS

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

PLEASE WRITE: DEPARTMENT OF CHEMICAL ENGINEERING
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720

CHEMICAL ENGINEERING AT



UCLA

FACULTY

D. T. Allen
R.L. Bell
(Visiting Professor)
Y. Cohen
T. H. K. Frederking
S. K. Friedlander
R. F. Hicks
E. L. Knuth
(Prof. Emeritus)
V. Manousiouthakis
H. G. Monbouquette
K. Nobe
L. B. Robinson
(Prof. Emeritus)
S. M. Senkan
O. I. Smith
W. D. Van Vorst
(Prof. Emeritus)
V. L. Vilker
A. R. Wazzan

PROGRAMS

UCLA's Chemical Engineering Department offers a program of teaching and research linking fundamental engineering science and industrial practice. Our Department has strong graduate research programs in environmental chemical engineering, biotechnology, and materials processing. With the support of the Parsons Foundation and EPA, we are pioneering the development of methods for the design of clean chemical technologies, both in graduate research and engineering education

Fellowships are available for outstanding applicants in both M.S. and Ph.D. degrees. A fellowship includes a waiver of tuition and fees plus a stipend.

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

RESEARCH AREAS

Thermodynamics and Cryogenics
Process Design and Process Control
Polymer Processing and Rheology
Mass Transfer and Fluid Mechanics
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

UNIVERSITY OF CALIFORNIA
SANTA BARBARA

• 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 ODETTE 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, Thermalhydraulics.
W. HENRY WEINBERG Ph.D. *(U.C. Berkeley)* • Surface Chemistry; Heterogeneous Catalysis; Electronic Materials
JOSEPH A. N. ZASADZINSKI Ph.D. *(Minnesota)* • Surface and Interfacial Phenomen, Structure of Microemulsions.

PROGRAMS AND FINANCIAL SUPPORT

The Department offers M.S. and Ph.D. degree programs Financial aid, including fellowships, teaching assistantships, and research assistantships, is available.

THE UNIVERSITY

One of the world's few seashore campuses, UCSB is located on the Pacific Coast 100 miles northwest of Los Angeles. The student enrollment is over 18,000. The metropolitan Santa Barbara area has over 150,000 residents and is famous for its mild, even climate.

For additional information and applications, write to

Chair
Graduate Admissions Committee
Department of Chemical and Nuclear Engineering
University of California
Santa Barbara, CA 93106

CHEMICAL ENGINEERING

at the

CALIFORNIA INSTITUTE OF TECHNOLOGY

"At the Leading Edge"

FACULTY

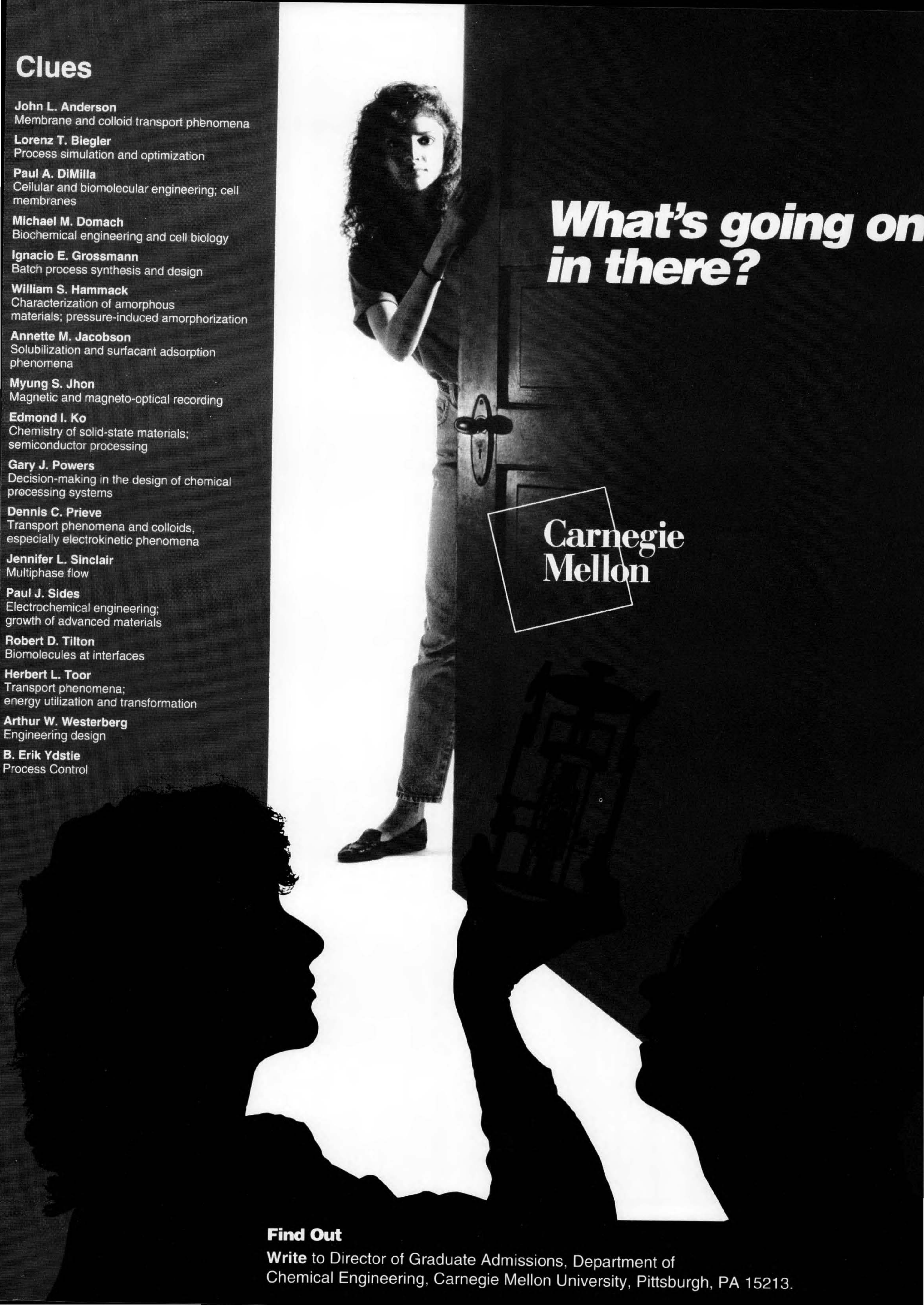
Frances H. Arnold
John F. Brady
Mark E. Davis
Richard C. Flagan
George R. Gavalas
Konstantinos P. Giapis
Julia A. Kornfield
Manfred Morari
C. Dwight Prater (Visiting)
John H. Seinfeld
Nicholas W. Tschoegl (Emeritus)
Zhen-Gang Wang

RESEARCH INTERESTS

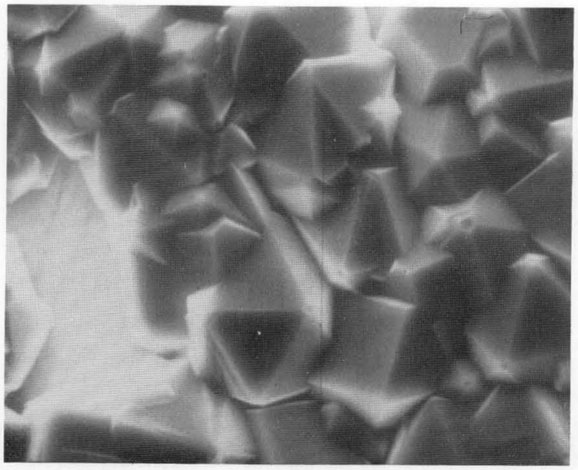
Aerosol Science
Applied Mathematics
Atmospheric Chemistry and Physics
Biocatalysis and Bioreactor Engineering
Bioseparations
Catalysis
Chemical Vapor Deposition
Combustion
Colloid Physics
Fluid Mechanics
Materials Processing
Microelectronics Processing
Microstructured Fluids
Polymer Science
Process Control and Synthesis
Protein Engineering
Statistical Mechanics of Heterogeneous Systems

• for further information, write •

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 amorphorization
Annette M. Jacobson
Solubilization and surfacant 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
What's going on in there?
Carnegie Mellon
Find Out
Write to Director of Graduate Admissions, Department of Chemical Engineering, Carnegie Mellon University, Pittsburgh, PA 15213.

Chemical Engineering in the 21st Century?



Diamond crystals synthesized by graduate student C. Kovach.

Want to learn what the future holds for chemical engineers?

Consider graduate study at

CASE WESTERN RESERVE UNIVERSITY

Opportunities for Innovative Research in

• Advanced Energy Conversion •
• Chemical/Biological Sensors •
• Intelligent Control •
• Micro- and Nano-Materials •
• Novel Separations/Processing •

For more information contact:

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, electrodeposition

Chung-Chiun Liu, Ph.D. 1968, Case Western Reserve University
Electrochemical sensors, electrochemical synthesis, electrochemistry 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

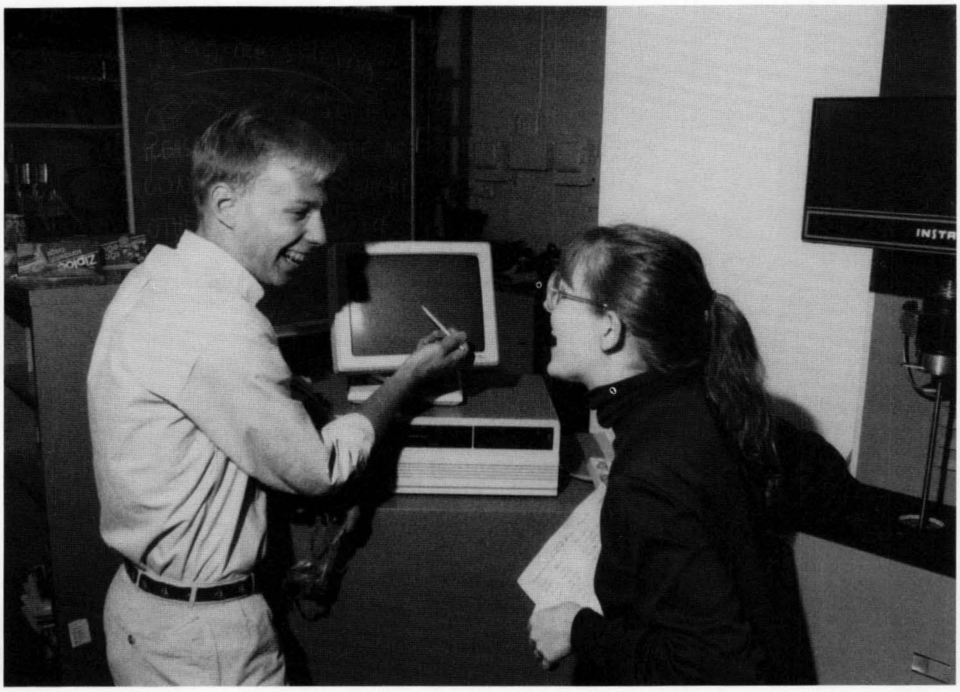
Syed Qutubuddin, Ph.D. 1983, Carnegie-Mellon University
Surfactant and polymer solutions, metal extraction, enhanced oil recovery

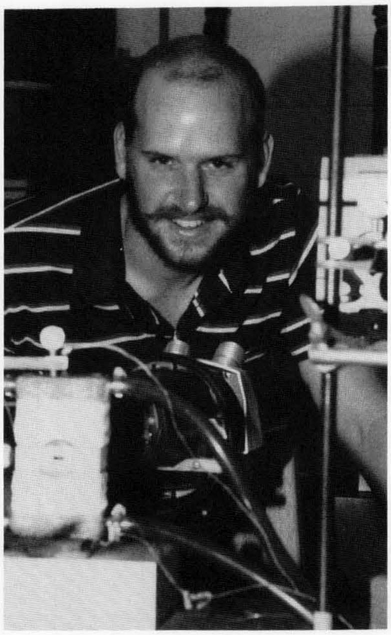
Robert F. Savinell, Ph.D. 1977, University of Pittsburgh
Applied electrochemistry, electrochemical system simulation and optimization, electrode processes

CASE WESTERN RESERVE UNIVERSITY

Graduate Study in

CHEMICAL ENGINEERING



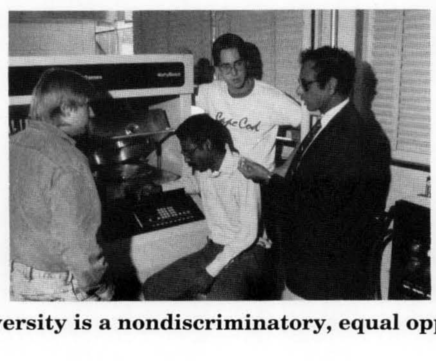


AT CLARKSON

- **CENTER FOR ADVANCED MATERIALS PROCESSING**
- **NASA CENTER FOR THE DEVELOPMENT OF COMMERCIAL CRYSTAL GROWTH IN SPACE**
- **INSTITUTE OF COLLOID AND SURFACE SCIENCE**

For details, please write to:

Dean of the Graduate School
Clarkson University
Potsdam, New York 13699



Clarkson University is a nondiscriminatory, equal opportunity, affirmative action educator and employer.

UNIVERSITY OF COLORADO
BOULDER

Graduate students in the Department of Chemical Engineering may also participate in the popular, interdisciplinary Biotechnology Training Program at the University of Colorado and in the interdisciplinary NSF Industry/University Cooperative Research Center for Separations Using Thin Films.

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

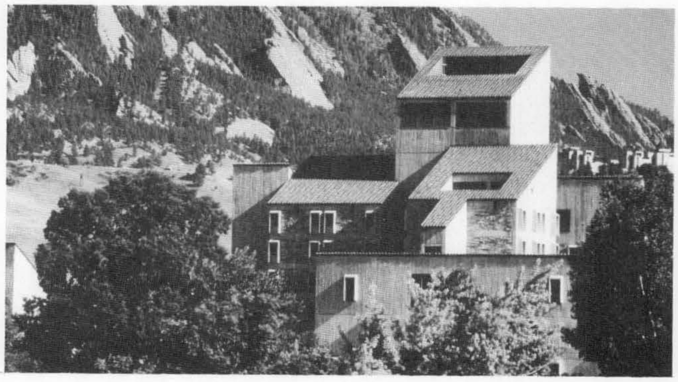
ROBERT L. SANI
Professor
Director of Center for Low-gravity Fluid Mechanics and Transport Phenomena
Ph.D., University of Minnesota, 1963

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
- Thermodynamics and Cryogenics
- Thin Films Science

FOR INFORMATION AND APPLICATION, WRITE TO

Director, Graduate Admissions Committee • Department of Chemical Engineering
University of Colorado, Boulder • Boulder, Colorado 80309-0424
•FAX (303) 492-4341

Research and Graduate Studies in Chemical Engineering

Florida A & M University/ Florida State University Joint College of Engineering

M.S. and Ph.D. Programs

Areas of Research and Research Interest

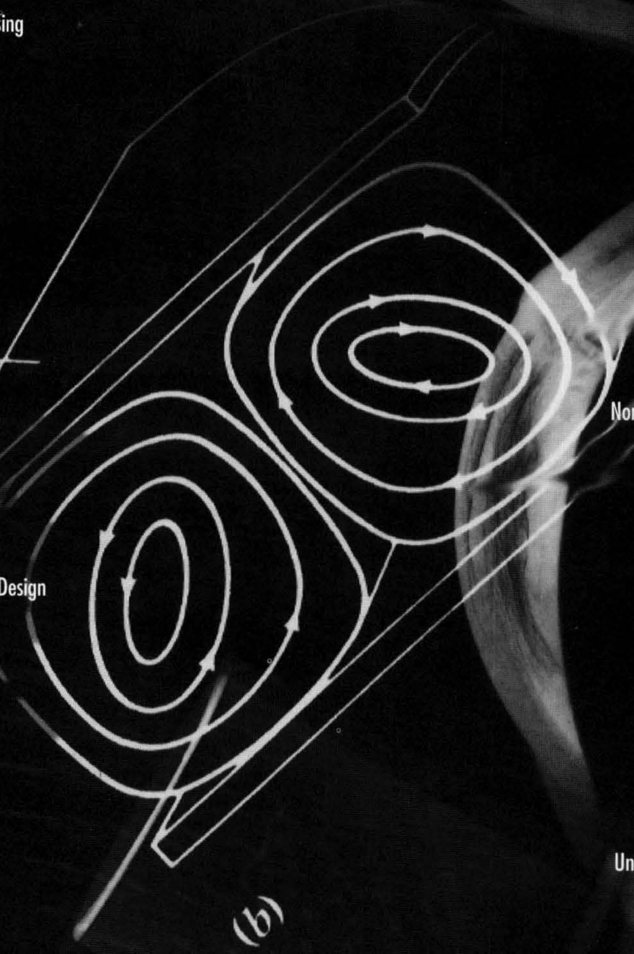
Advanced Materials (Ceramics, Colloids, and Polymers)
- Brownian Motion
- Chemical Vapor Deposition
- Composite Materials
- Complex Fluids
- Phase Transitions
- Macromolecular Phenomena
- Macromolecular Transport in Polymer Gel Media
- Polymer Processing
- Semiconductor and Superconductor Processing
- 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



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

*Afiliate Faculty

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

Georgia Tech

CHEMICAL ENGINEERING

The Faculty and Their Research

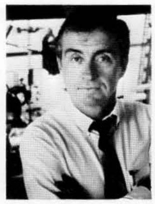

A.S. Abhiraman
Polymer science and engineering


Pradeep K. Agrawal
Heterogeneous catalysis, surface chemistry, reaction kinetics


Yaman Arkun
Process design and control, spouted-bed reactors


Sue Ann Bidstrup
Microelectronics, polymer processing

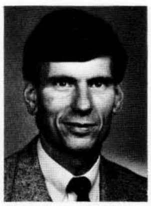

Charles A. Eckert
Molecular thermodynamics, chemical kinetics, separations


William R. Ernst
Reactor design, catalysis


Larry J. Forney
Mechanics of aerosols, buoyant plumes and jets


Charles W. Gorton
Heat transport phenomena, fluidization


Jeffrey S. Hsieh
Pulp and paper


Paul A. Kohl
Photochemical processing, chemical vapor deposition

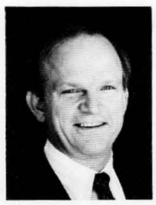

Michael J. Matteson
Aerocolloidal systems, interfacial phenomena, fine-particle technology

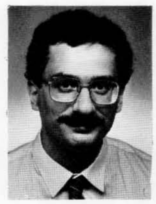

John D. Muzzy
Polymer engineering, energy conservation, economics


Robert M. Nerem
Biomechanics, mammalian cell cultures


Gary W. Poehlein
Emulsion polymerization, latex technology


Ronnie S. Roberts
Biochemical engineering, mass transfer, reactor design


Ronald W. Rousseau
Separation processes, crystallization


Athanassios Sambanis
Biochemical engineering, microbial and animal cell cultures


Robert J. Samuels
Polymer science and engineering


F. Joseph Schork
Reactor engineering, process control, polymerization reactor dynamics


A. H. Peter Skelland
Mass transfer, extraction, mixing, non-Newtonian flow


Jude T. Sommerfeld
Process design and simulation


D. William Tedder
Process synthesis and simulation, chemical separation, waste management, resource recovery


Amyn S. Teja
Thermodynamic and transport properties, phase equilibria, supercritical gas extraction


Mark G. White
Catalysis, kinetics, reactor design


Timothy M. Wick
Biochemical engineering, cell-cell interactions, biofluid dynamics


Jack Winnick
Electrochemical engineering, thermodynamics, air pollution control


Ajit P. Yoganathan
Biofluid dynamics, rheology, transport phenomena

For more information, Contact:
Professor Ronald W. Rousseau, Director
School of Chemical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0100
(404) 894-2867

UIC **The University of Illinois at Chicago**
Department of Chemical Engineering

• MS and PhD Graduate Program •

FACULTY

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

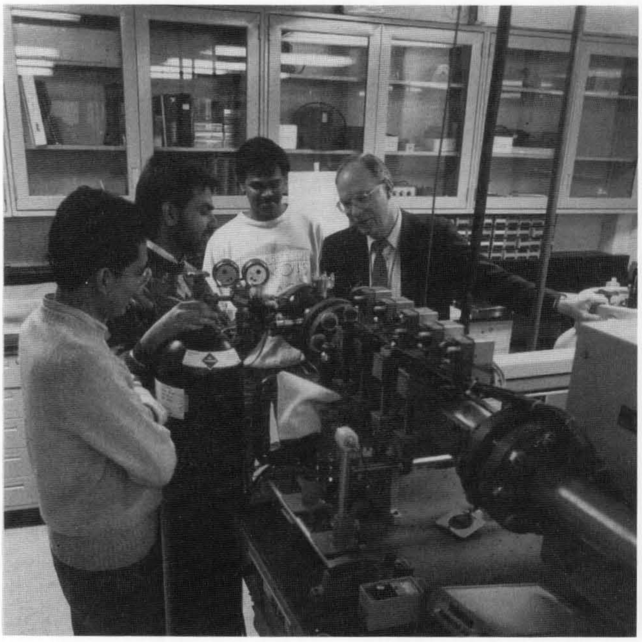
Satish C. Saxena
Ph.D., Calcutta University, 1956
Professor

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
Director of Graduate Studies • Department of Chemical Engineering
University of Illinois at Chicago • Box 4348 • Chicago, IL 60680 • (312) 996-3424

GRADUATE STUDY IN CHEMICAL ENGINEERING AT

Illinois Institute of Technology

THE UNIVERSITY

- Private, coeducational and research university
- 4800 undergraduate students
- 5400 graduate students
- 3 miles from downtown Chicago and 1 mile west of Lake Michigan
- Campus recognized as an architectural landmark

THE CITY

- One of the largest cities in the world
- National and international center of business and industry
- Enormous variety of cultural resources
- Excellent recreational facilities
- Industrial collaboration and job opportunities

THE DEPARTMENT

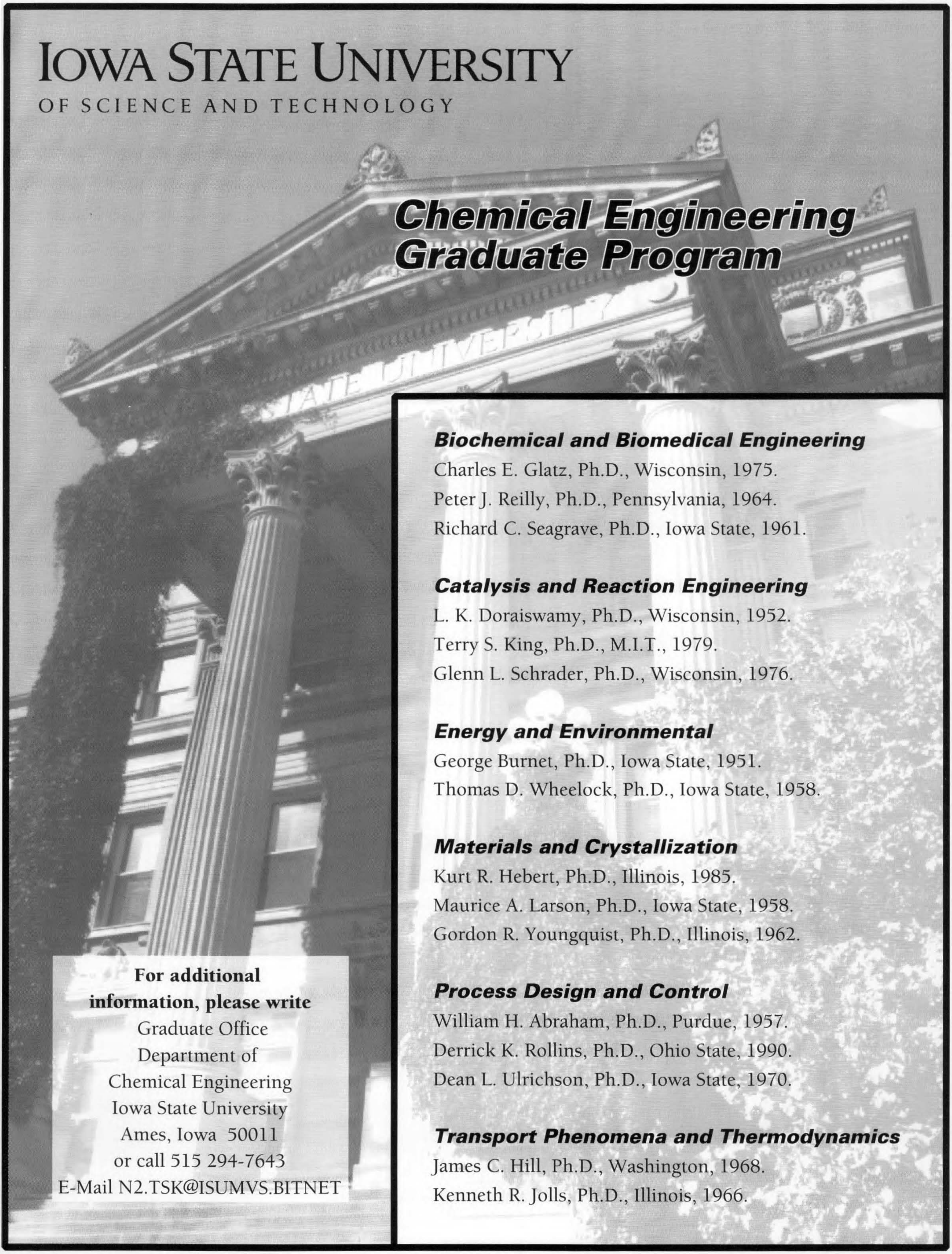
- One of the oldest in the nation
- Approximately 40 full-time and 40 part-time graduate students
- M.Ch.E., M.S., and Ph.D. degrees
- Financially attractive fellowships and assistantships available to outstanding students

THE FACULTY

- *HAMID ARASTOOPOUR (Ph.D., IIT)*
  Multiphase flow and fluidization, powder and material processing, environmental engineering
- *RICHARD A. BEISSINGER (D.E.Sc., Columbia)*
  Transport processes in chemical and biological systems, rheology of polymeric and biological fluids
- *ALI CINAR (Ph.D., Texas A & M)*
  Chemical process control, distributed parameter systems, expert systems
- *DIMITRI GIDASPOW (Ph.D., IIT)*
  Hydrodynamics of fluidization, multiphase flow, separations processes
- *HENRY R. LINDEN (Ph.D., IIT)*
  Energy policy, planning, and forecasting
- *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)*
  Polymer composite materials and plastic recycling
- *DAVID C. VENERUS (Ph.D., Pennsylvania State U)*
  Polymer rheology and processing, and transport phenomena
- DARSH T. WASAN (Ph.D., California-Berkeley)
  Interfacial phenomena, separation processes, enhanced oil recovery

• APPLICATIONS •

Dr. A. Cinar
Graduate Admissions Committee
Department of Chemical Engineering
Illinois Institute of Technology
I.I.T. Center
Chicago, IL 60616


IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY
Chemical Engineering
Graduate Program
Biochemical and Biomedical Engineering
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

Graduate Study and Research in

Chemical Engineering

TIMOTHY A. BARBARI

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

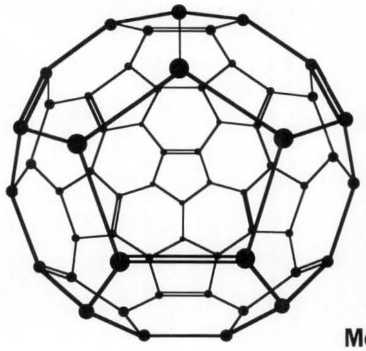
For further information contact:

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

E.O.E./A.A.

University of Kentucky

Far From An Ordinary Ball



Research with advanced materials (carbon fibers, nitride catalysts, superconducting thin films, and liquid crystalline polymers) and with Buckyballs is ongoing here in Lexington.

Anything But An Ordinary University

At the University of Kentucky—designated by the Carnegie Foundation as a Research University of the First Class, and included in the NSF's prestigious listing of Top 100 research institutions in America—*CHOICES* for Chem. E. graduate students are anything but ordinary. There are joint projects with Pharmacy, the Medical School, the Markey Cancer Center, and Chemistry researchers. And abundant opportunities for intense interaction with extraordinary faculty, as well as access to state-of-the-art facilities and equipment, including an IBM ES 3900/600J Supercomputer.

With Out-Of-The-Ordinary Chem. E. Specialties

Aerosol Chemistry and Physics—Weighing picogram particles in electrodynamic balance, measuring monolayer adsorption, data with seven significant figures.

Cellular Bioengineering—Rheological and transport properties of cell membranes; cell adhesion, cancer research, transport of drugs across membranes, and membrane biofouling.

Computational Engineering—Modeling turbulent diffusion in atmospheric convective boundary layers; modeling growth of multi-component aerosol systems.

Environmental Engineering—EPA-approved analytical laboratory; global atmospheric transport models; atmospheric photochemistry; control of heavy metals and hazardous organics; water pollution research.

Membrane Science—Development of low pressure charged membranes; thin film composite membranes; development of bio-functional synthetic membranes.

From A Uniquely Un-Ordinary Faculty

Ph.D.

Recent national awards won by our faculty include: Larry K. Cecil AIChE Environmental Division; AIChE Outstanding Counselor Award, 1983, 1991; ASM Henry Marion Howe Medal; AAAR Kenneth T. Whitby Memorial Award; BMES Dr. Harold Lamport Award for a Young Investigator; and two NSF-Presidential Young Investigators. Recent University-wide awards by faculty include: Great Teacher; Research Professor; Excellence in Undergraduate Education; and Alumni Professor.

All Of Which Create Some Extraordinary Opportunities For You

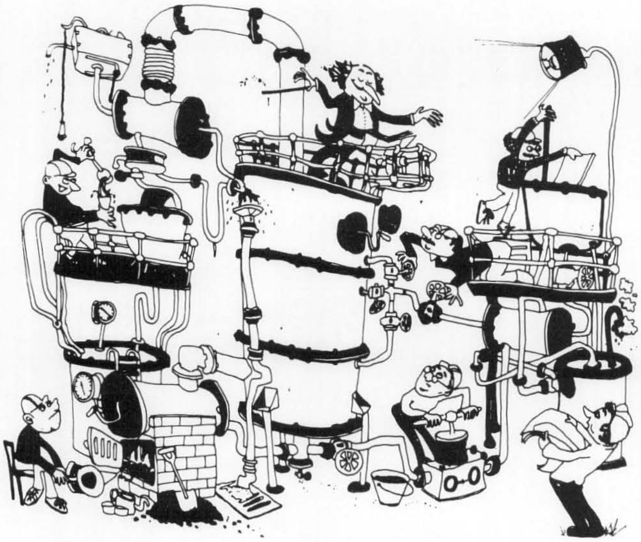
Doctoral incentives well worth your consideration: Up to $20,000 per year stipends plus tuition, books, research supplies, travel allowances. Interested in obtaining a degree of extraordinary worth? Contact **Dr. R.I. Kermode, Department of Chemical Engineering, University of Kentucky, Lexington, KY 40506-0046.**

606-257-4956

University of Kentucky Department of Chemical Engineering

LOUISIANA STATE UNIVERSITY

CHEMICAL ENGINEERING GRADUATE SCHOOL



THE CITY

Baton Rouge is the state capitol 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

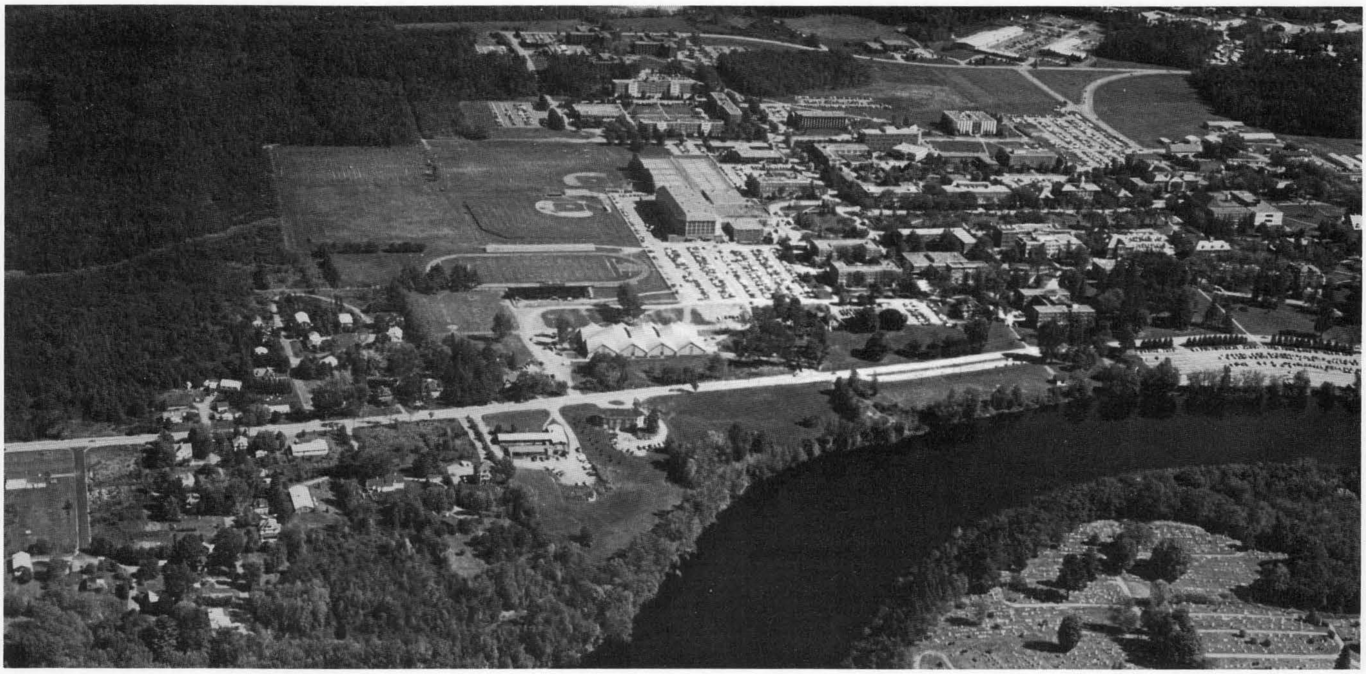
R.D. WESSON (Ph.D., University of Michigan)
Semi-Crystalline Polymer Processing

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 opportunites, 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

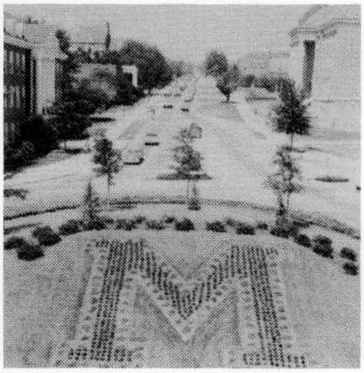
Doug Bousfield
Department of Chemical Engineering
Jenness Hall, Box B • University of Maine
Orono, Maine 04469-0135
(207) 581-2300

GRADUATE STUDY IN BIOCHEMICAL ENGINEERING

FOR ENGINEERING AND SCIENCE MAJORS

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:

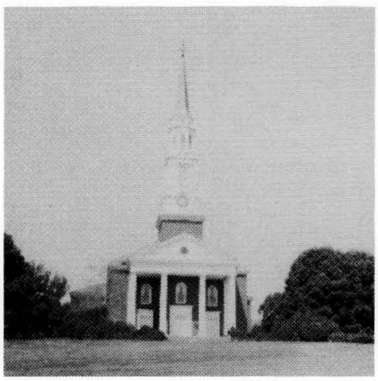
William E. Bentley
Richard V. Calabrese
Kyu Yong Choi
Larry L. Gasner
James W. Gentry
Michael L. Mavrovouniotis
Thomas J. McAvoy
Thomas M. Regan
Theodore G. Smith
Nam Sun Wang
William A. Weigand
Evanghelos Zafiriou

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:

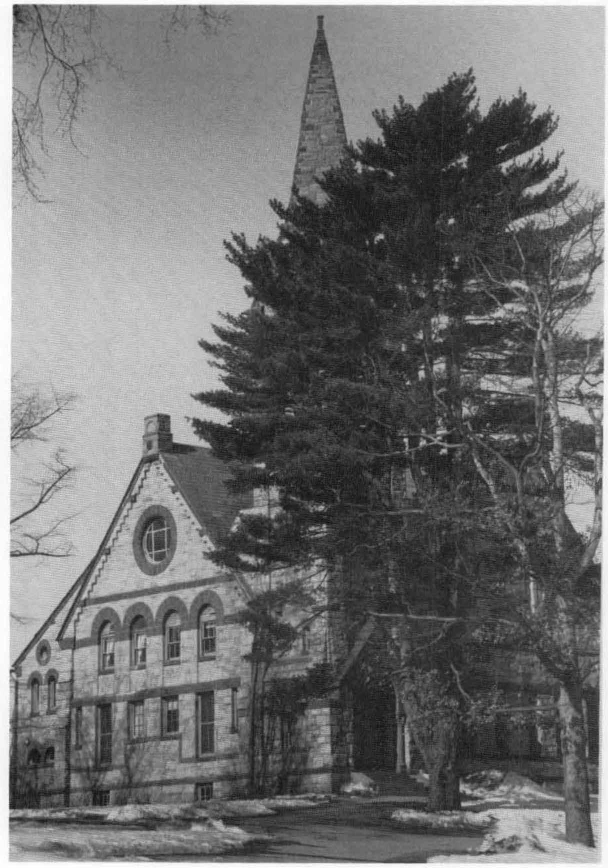
Chemical Engineering Graduate Studies
Department of Chemical Engineering
University of Maryland
College Park, MD 20742-2111

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.

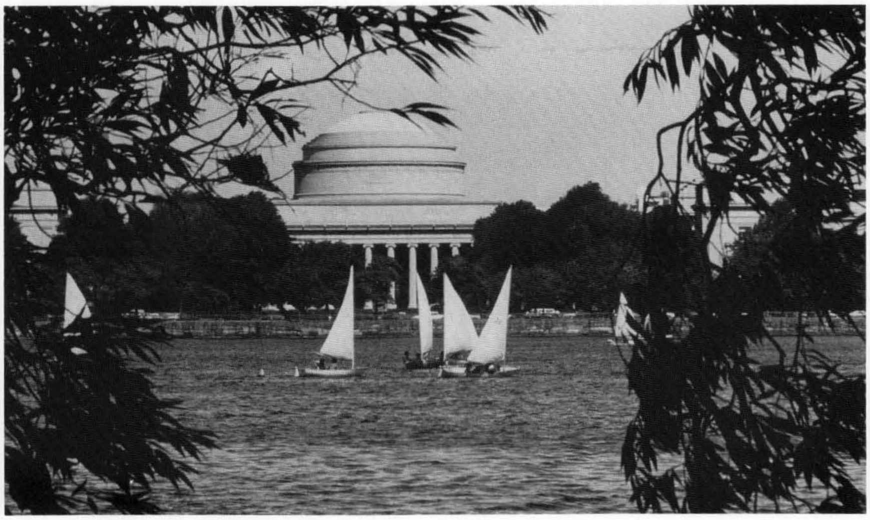
For application forms and further information on fellowships and assistantships, academic and research programs, and student housing, write:

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

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

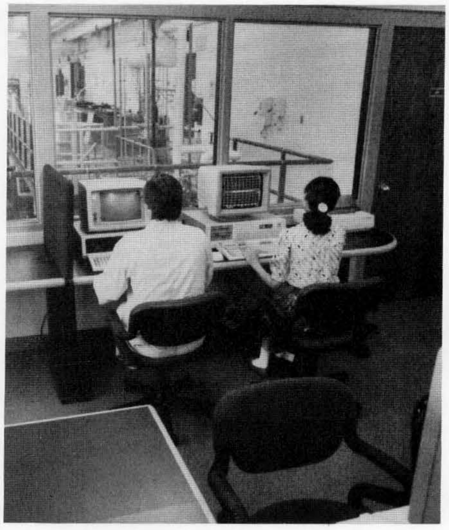
B. W. WILKINSON, Professor Emeritus
Ph.D., 1958, Ohio State University
Energy Systems and Environmental Control, Nuclear Reactor, Radioisotope Applications

R. M. WORDEN
Ph.D., 1986, University of Tennessee
Biochemical Engineering, Immobilized Cell Technology, Food Engineering

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

MSU is an Affirmative Action/Equal Opportunity Institution

Michigan Technological University

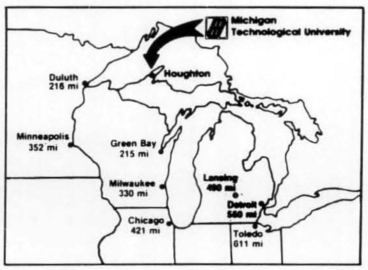


Add your name to the ranks of the prestigious engineering alumni from Michigan Tech

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

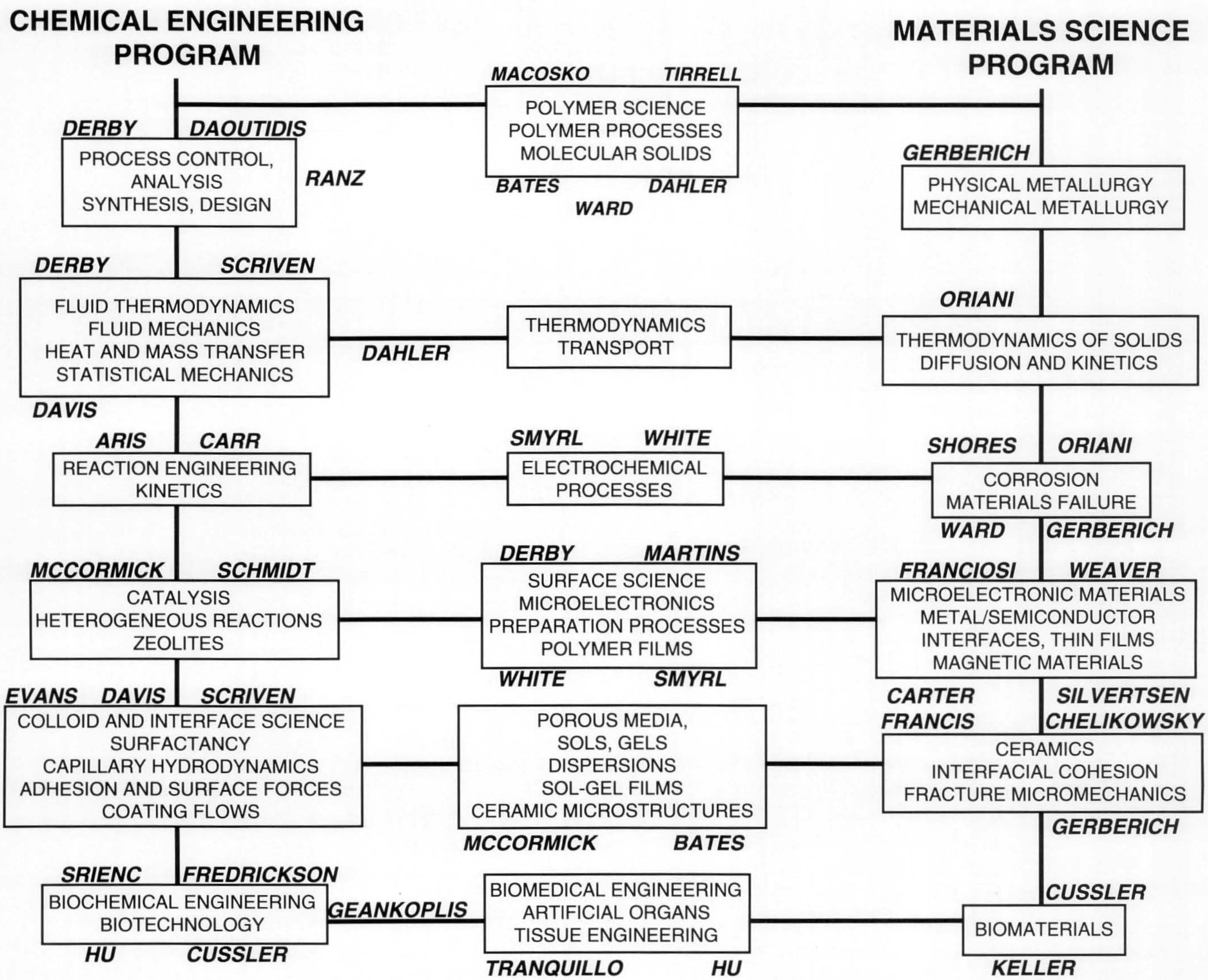
Surface science, sol-gel processing
Michael E. Mullins, Associate Professor
Ph.D., Rochester, 1983

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.

UNIVERSITY OF MINNESOTA

Chemical Engineering and Materials Science



THE FACULTY

R. Aris	H.T. Davis	K.H. Keller	J.M. Sivertsen
F.S. Bates	J.J. Derby	C.W. Macosko	W.H. Smyrl
R.W. Carr, Jr.	D.F. Evans	J.L. Martins	F. Srienc
C. B. Carter	A. Franciosi	A.V. McCormick	M. Tirrell
J.R. Chelikowsky	L.F. Francis	R.A. Oriani	R. Tranquillo
E.L. Cussler	A.G. Fredrickson	W.E. Ranz	M.D. Ward
J.S. Dahler	C.J. Geankoplis	L.D. Schmidt	J.H. Weaver
P. Daoutidis	W.W. Gerberich	L.E. Scriven	H.S. White
	W-S. Hu	D.A. Shores	

For information and application forms, write:

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

Department of Chemical Engineering

UMR

MISSOURI'S TECHNOLOGICAL UNIVERSITY

UNIVERSITY OF MISSOURI-ROLLA

M.S. and Ph.D. Degrees

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

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*

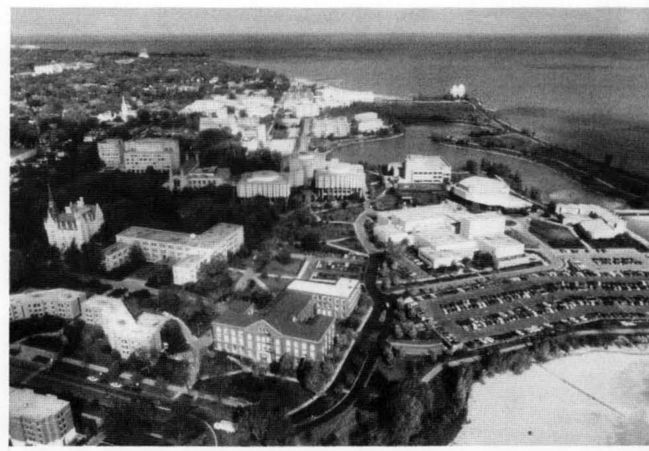
C. John Setzer, Assoc. Head (Ohio State) — *Plant and Process Economics and Management*

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

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. Banchero
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

The University of Oklahoma

GRADUATE STUDIES IN CHEMICAL ENGINEERING AND MATERIALS SCIENCE

You want unlimited opportunities & the good life. We offer innovation at the forefront of a rewarding profession. We could have a very good working relationship. Let's talk about it.

Call us: (405) 325-5811
Fax us: (405) 325-5813
Or write:

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

TM

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 • endothellium/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

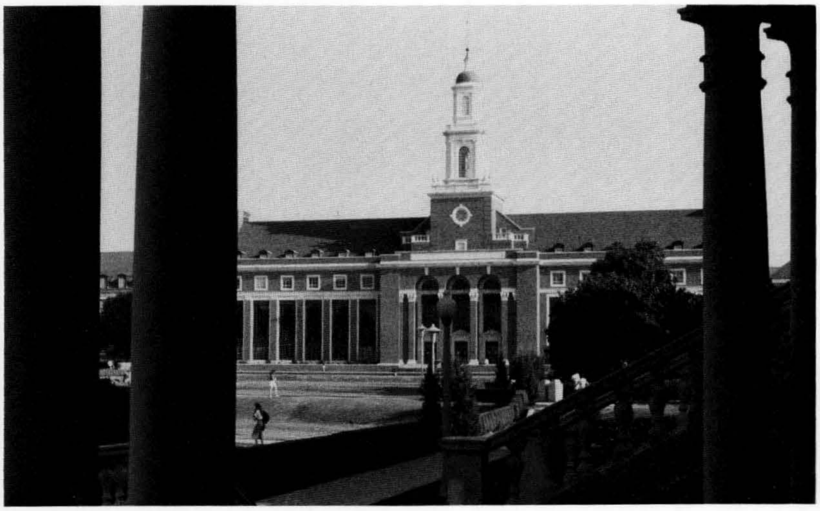
John F. Scamehorn, George Lynn Cross Research Professor. *Chemical Engineering:* • surface and colloid science • tertiary oil recovery • detergency • membrane separations • adsorption • pollution control • polymers

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

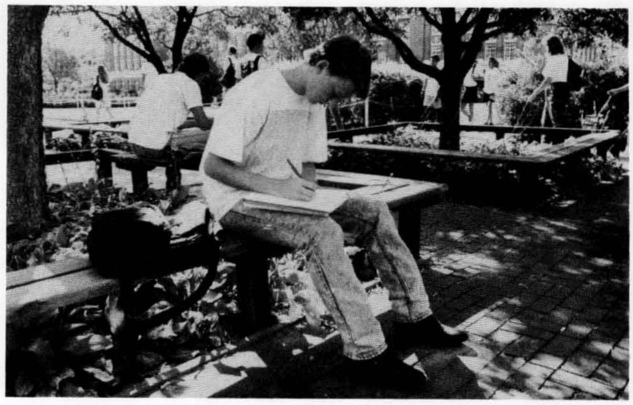
Kenneth E. Starling, George Lynn Cross Research Professor. *Chemical Engineering:* • equation of state development and prediction of thermodynamic and phase behavior • equilibrium and non-equilibrium molecular theory of fluids • correlation of transport properties • process simulation • low temperature difference cycles • geothermal, ocean thermal, solar and wastewater heat energy conversion

Oklahoma State University

"Where People Are Important"



OSU's School of Chemical Engineering offers programs leading to M.S. and Ph.D. degrees. Qualified students receive financial assistance at nationally competitive levels.



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)

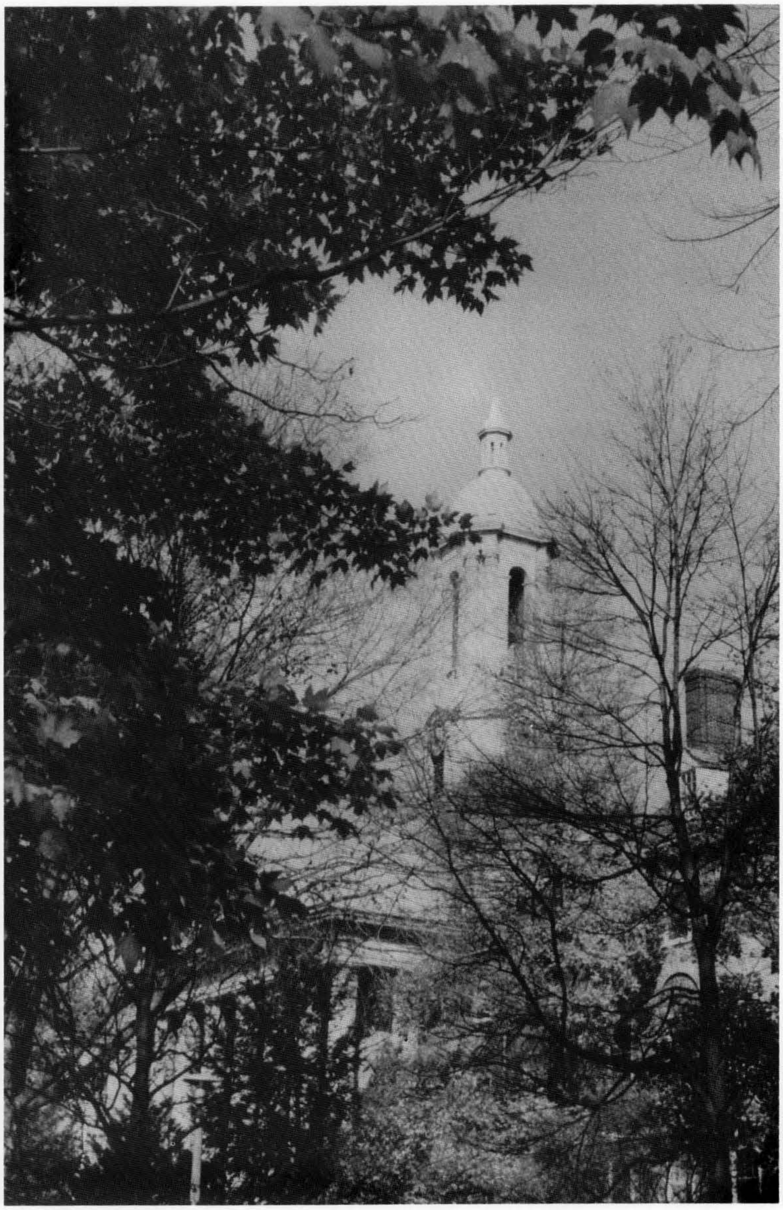
Research Areas

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

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

Rice University

Graduate Study in Chemical Engineering

The University

- Privately endowed coeducational school
- 2600 undergraduate students
- 1300 graduate students
- Quiet and beautiful 300-acre tree-shaded campus
- 3 miles from downtown Houston
- Architecturally uniform and aesthetic campus

The City

- Large metropolitan and cultural center
- Petrochemical capital of the world
- Industrial collaboration and job opportunities
- World renowned research and treatment medical center
- Professional sports
- Close to recreational areas

Applications and Inquiries

Chairman, Graduate Committee
Department of Chemical Engineering
PO Box 1892
Rice University
Houston, TX 77251

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

JOIN US

Graduate Study and Research leading to M.S. and Ph.D. degrees

Fellowships to $14,500

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

J. JORNE, Ph.D. 1972, California (Berkeley)
Electrochemical Engineering, Microelectronics Processing, Theoretical Biology

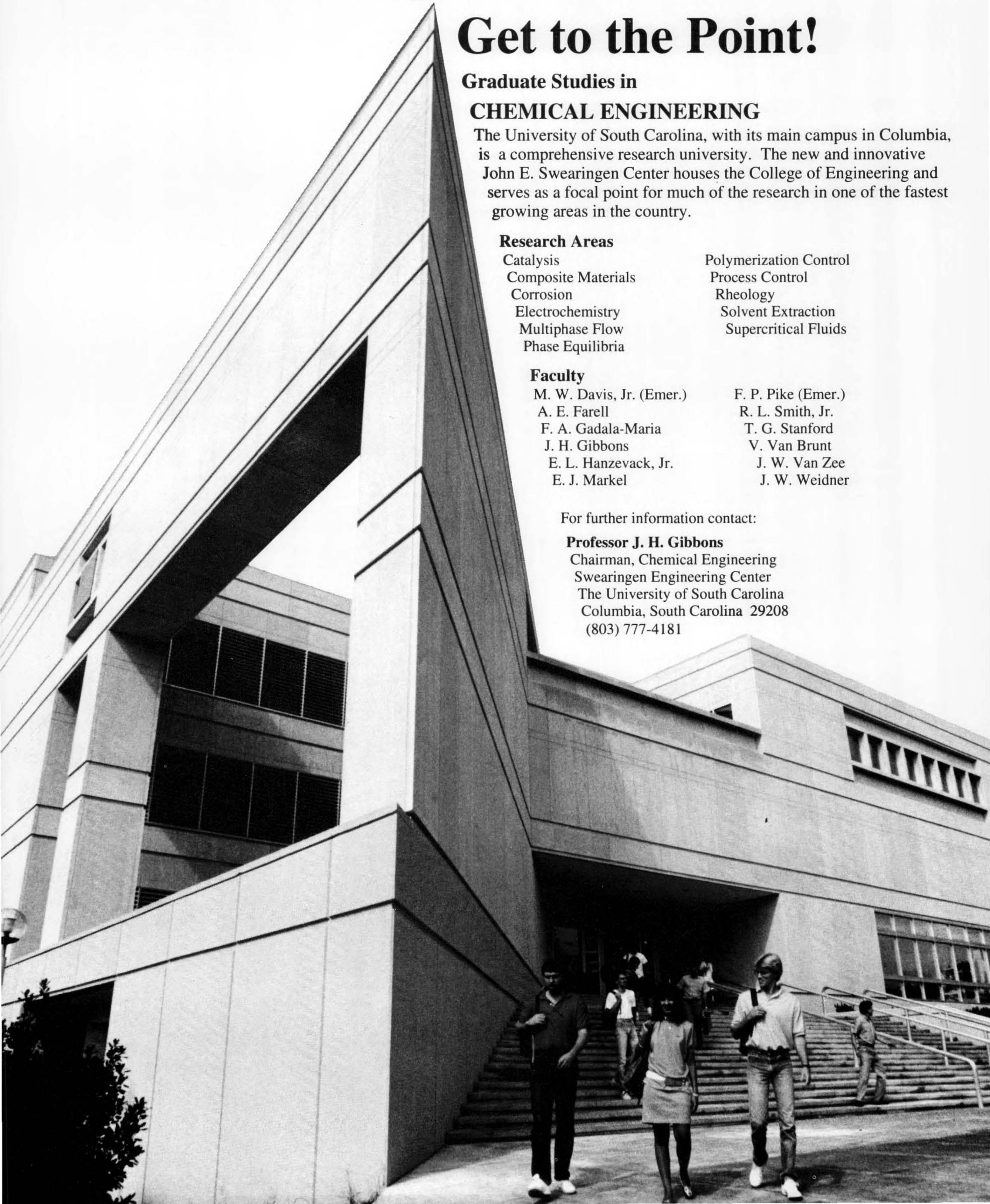
R. H. NOTTER, Ph.D. 1969, Washington (Seattle)
M.D. 1980, Rochester
Biomedical Engineering, Lung Surfactant, Molecular Biophysics

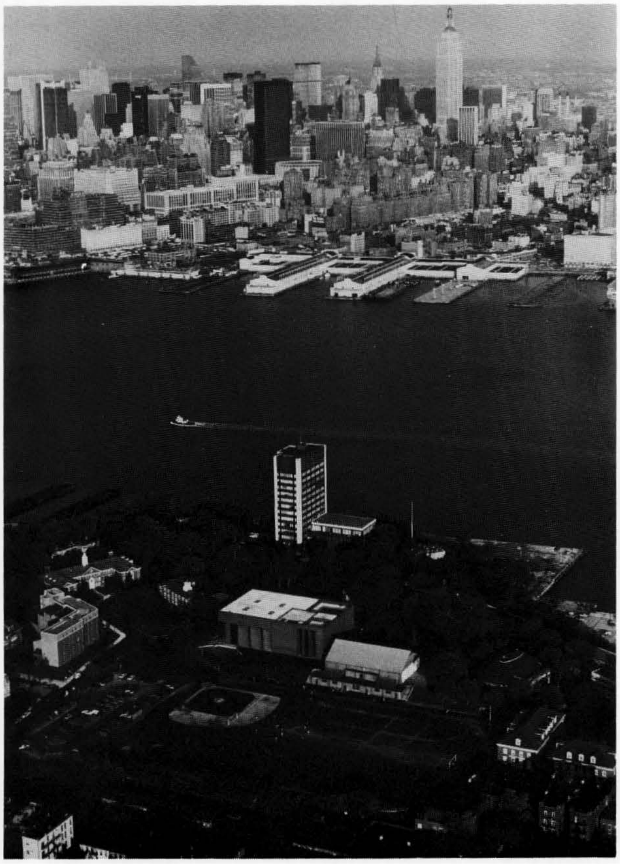
H. J. PALMER, Ph.D. 1971, Washington (Seattle)
Interfacial Phenomena, Phase Transfer Reactions, Mass Transfer, Bioengineering

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





STEVENS
INSTITUTE OF TECHNOLOGY

- *Multidisciplinary department consisting of chemical and polymer engineering, chemistry, and biology*
- *Beautiful campus on the Hudson River overlooking metropolitan New York City*
- *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 Pitsburgh)
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

Full and part-time
Day and evening programs

- **MASTERS**
- **CHEMICAL ENGINEER**
- **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

Inquiries should be sent to:
Graduate Advisor • Department of Chemical Engineering
The University of Texas • Austin, Texas 78712
(512) 471-6991

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

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

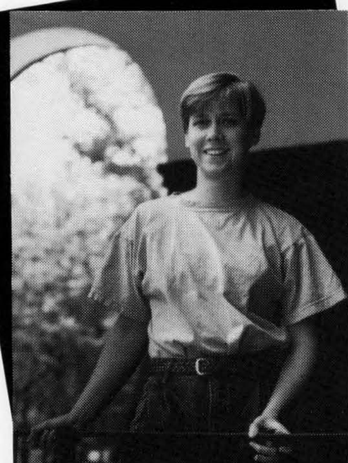
John L. Hudson • *Ph.D., Northwestern University* • Dynamics of chemical reactors, electrochemical and multiphase reactors

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

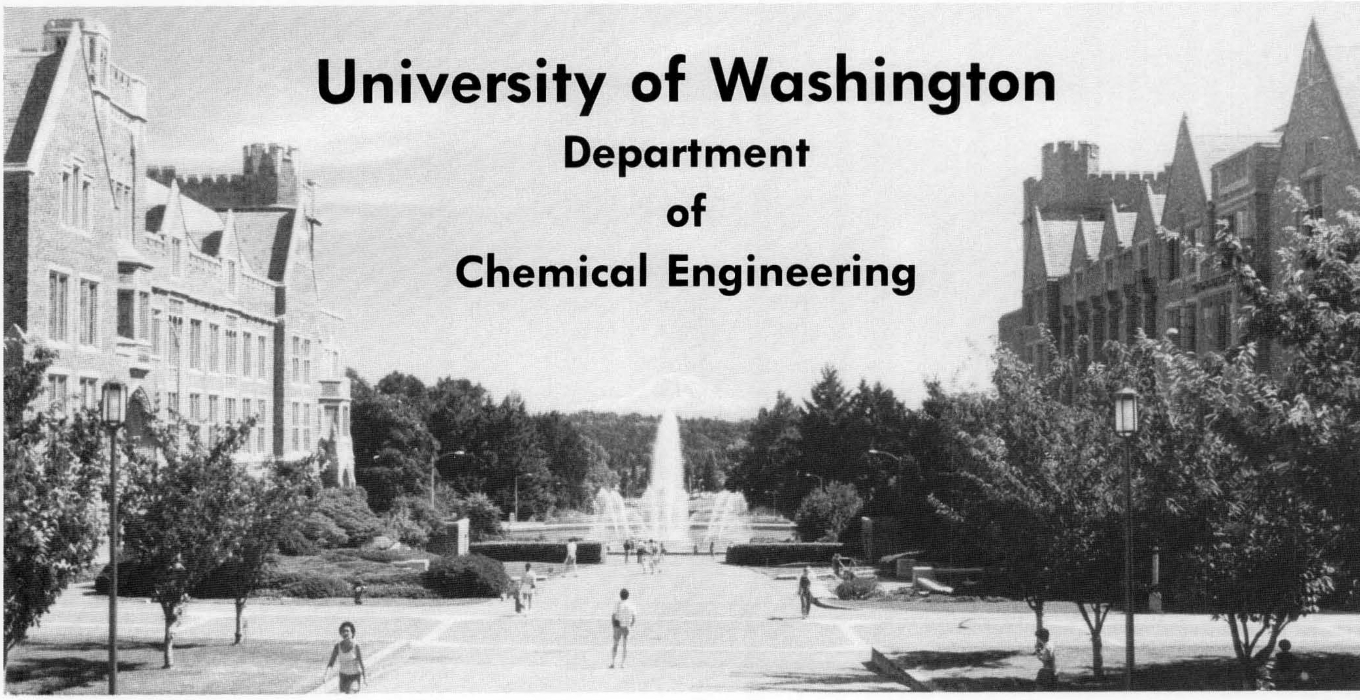
Lembit U. Lilleleht • *Ph.D., University of Illinois* • Fluid mechanics, heat transfer, multiphase systems, alternative energy

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.



- 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

François Baneyx, Ph.D., Texas (Austin)	Biotechnology; Protein Technology; Biochemical Engineering
John C. Berg, Ph.D., California (Berkeley)	Interfacial Phenomena; Surface and Colloid Science
E. James Davis, Ph.D., Washington	Colloid Science; Aerosol Chemistry and Physics; Electrokinetics
Bruce A. Finlayson, Ph.D., Minnesota	Mathematical Modeling
William J. Heideger, Ph.D., Princeton	Mass Transfer
Bradley R. Holt, Ph.D., Wisconsin	Process Design and Control
Barbara Krieger-Brockett, Ph.D., Wayne State	Reaction Engineering
N. Lawrence Ricker, Ph.D., California (Berkeley)	Process Control and Optimization
J. W. Rogers, Jr., Ph.D., Texas (Austin)	Surface Science; Thin-Film Deposition
Daniel T. Schwartz, Ph.D., California (Davis)	Electrochemical Engineering; Electrolytic Thin-Film Science
James C. Seferis, Ph.D., Delaware	Polymeric Composites
Eric M. Stuve, Ph.D., Stanford	Catalytic and Electrochemical Surface Science
Lewis E. Wedgewood, Ph.D., Wisconsin	Polymer Rheology

Research Faculty

David G. Castner, Ph.D., California (Berkeley) • Biomaterials; Surface Science

Adjunct and Joint Faculty Active in Department Research

G. Graham Allan, Ph.D., D.Sc., Glasgow	Fiber and Polymer Science
Albert L. Babb, Ph.D., Illinois	Biomedical Engineering; Hemodialysis
Kermit L. Garlid, Ph.D., Minnesota	Nuclear Engineering; Radioactive Waste
Richard R. Gustafson, Ph.D., Washington	Pulp and Paper
Allan S. Hoffman, Sc.D., MIT	Biomaterials in Medicine and Biotechnology
Thomas A. Horbett, Ph.D., Washington	Biomaterials; Peptide Drug Delivery
William T. McKean, Ph.D., Washington	Pulp and Paper Science
Buddy D. Ratner, Ph.D., Brooklyn Polytechnic	Biomaterials; Polymers; Surface Characterization
Gene L. Woodruff, Ph.D., MIT	Nuclear Engineering

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 interest 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.

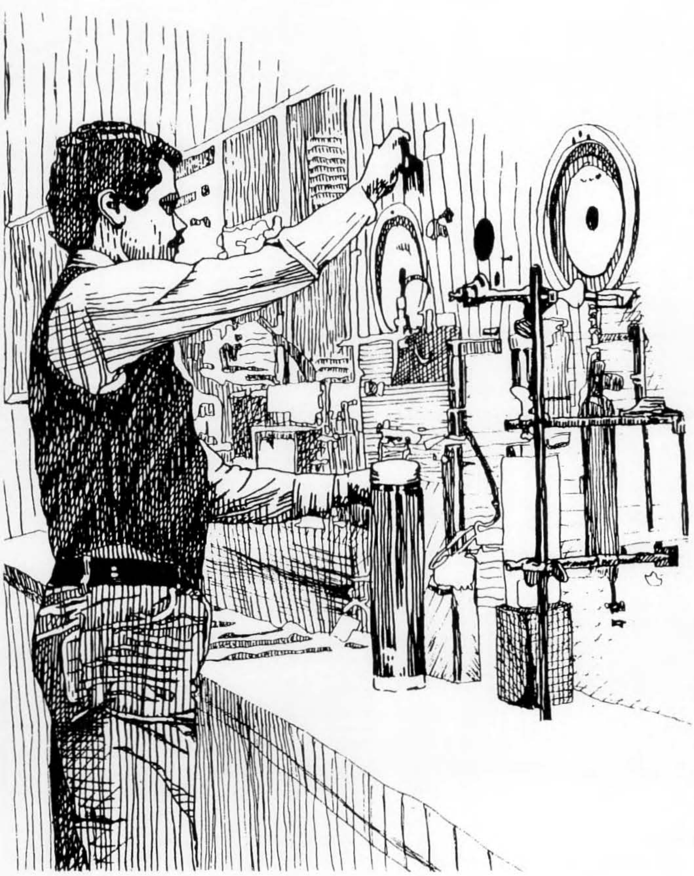
FACULTY AND RESEARCH INTERESTS

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 precursers, 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

West Virginia University

Chemical Engineering

FACULTY

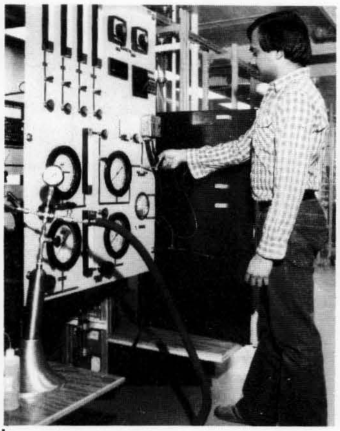
Richard C. Bailie *(Iowa State University)*
Eugene V. Cilento, Chairman *(University of Cincinnati)*
Dady B. Dadyburjor *(University of Delaware)*
Rakesh K. Gupta *(University of Delaware)*
Hisashi O. Kono *(Kyushu University)*
Edwin L. Kugler *(Johns Hopkins University)*
Joseph A. Shaeiwitz *(Carnegie-Mellon 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



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, policitical 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

Brown University

Graduate Study in Chemical Engineering

Faculty

Joseph M. Calo, Ph.D. (Princeton)
Bruce Caswell, Ph.D. (Stanford)
Richard A. Dobbins, Ph.D. (Princeton)
Sture K. F. Karlsson, Ph.D. (Johns Hopkins)
Joseph D. Kestin, D.Sc. (University of London)
Joseph T.C. Liu, Ph.D. (California Institute of Technology)
Edward A. Mason, Ph.D. (Massachusetts Institute of Technology)
T. F. Morse, Ph.D. (Northwestern)
Peter D. Richardson, Ph.D., D.Sc. Eng. (University of London)
Merwin Sibulkin, A.E. (California Institute of Technology)
Eric M. Suuberg, Sc.D. (Massachusetts Institute of Technology)
Stephen L. Woodruff, Ph.D. (University of Michigan)

Research Topics in Chemical Engineering

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

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

For further information write:

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

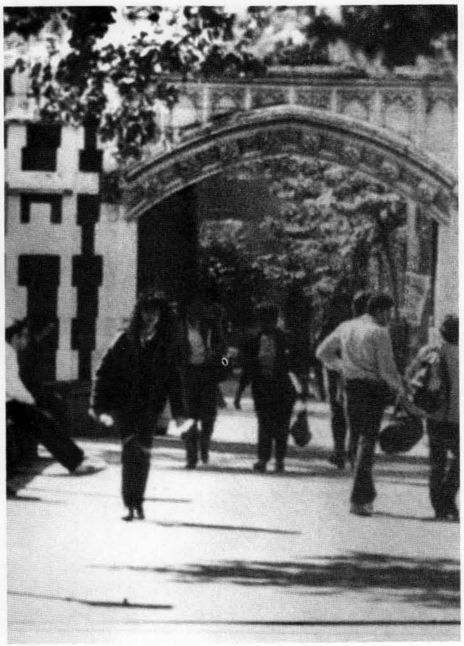
The University of California, San Diego

Graduate Programs in Chemical Engineering leading to the M.S. and Ph.D. Degrees

Located in a park-like setting high on the bluffs overlooking the Pacific Ocean at La Jolla, UCSD is recognized today as a major center for innovation in science and technology. The Chemical Engineering Program, established in 1979, exists as a formal program within the large, broad-based engineering department, the Department of Applied Mechanics and Engineering Sciences.

The Faculty	Research Areas
Pao C. Chau	Biochemical Engineering
Joe D. Goddard	Mechanics and Transport Processes
Richard K. Herz	Catalysis, Chemical Reaction Engineering
Stanley Middleman	Fluid Dynamics
David R. Miller	Gas/Surface Interactions and Gas Dynamics
C. Pozrikidis	Fluid Mechanics
K. Seshadri	Reactive Gas Flows
Jan B. Talbot	Electrochemical Engineering
Jack L. White	Materials Engineering

For further information, please write: Graduate Student Affairs 0413 • Department of AMES/Chemical Engineering University of California, San Diego • 9500 Gilman Drive • La Jolla, CA 92093-0310



UNIVERSITY OF SOUTH FLORIDA

TAMPA, FLORIDA 33260

Graduate Programs in Chemical Engineering Leading to M.S. and Ph.D. Degrees

For further information contact:

Graduate Program Coordinator
Chemical Engineering
University of South Florida
Tampa, Florida 33620

(813) 974-3997

Faculty

V. R. Bhethanabotla
J. C. Busot
S. W. Campbell
L. H. Garcia-Rubio
R. A. Gilbert
W. E. Lee
J. A. Llewellyn
C. A. Smith
A. K. Sunol

Research Areas

Artificial Intelligence
Automatic Process Control
Biomaterials / Biocompatibility
Biomedical Engineering
Computer Aided Process Engineering
Computer Simulation
Irreversible Thermodynamics
Mathematic Modeling
Molecular Thermodynamics
Phase Equilibria
Physical Property Correlation
Polymer Reaction Engineering
Process Identification
Process Monitoring and Analysis
Sensors and Instrumentation
Statistical Mechanics
Supercritical Fluid Technology

UNIVERSITY OF SOUTHERN CALIFORNIA

GRADUATE STUDY IN CHEMICAL ENGINEERING

Please write for further information about the program, financial support, and application forms to:

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

• FACULTY •

W. VICTOR CHANG
(Ph.D., Ch.E., Caltech, 1976) • Physical properties of polymers and composites; adhesion; finite element analysis

ELMER L. DOUGHERTY, JR.
(Ph.D., Ch.E., Illinois, Urbana, 1955) • Optimization of oil and gas producing operations; simulation of hydrocarbon reservoir behavior; energy and environmental economics

IRAJ ERSHAGHI
(Ph.D., PTE, Southern Cal, 1972) • Well test analyses of fractured, geothermal, and gas storage reservoirs; reservoir characterization; petrophysical modeling

RONALD G. MINET
(Ph.D., Ch.E., New York University, 1959) *(Adjunct)* • Computer aided chemical process and plant design; catalysis; ceramic membranes

CORNELIUS J. PINGS
(Ph.D., Ch.E., Caltech, 1955) • Thermodynamics; statistical mechanics and liquid state physics *(Provost and Senior Vice President, Academic Affairs)*

MUHAMMAD SAHIMI
(Ph.D., Ch.E., Minnesota, 1984) • Transport and mechanical properties of disordered systems; percolation theory and non-equilibrium growth processes; flow, diffusion, dispersion and reaction in porous media

RONALD SALOVEY
(Ph.D., Phys. Chem., Harvard, 1958) • Physical chemistry and irradiation of polymers; characterization of elastomers and filled systems; polymer crystallization

KATHERINE S. SHING
(Ph.D., Ch.E., Cornell, 1982) • Thermodynamics and statistical mechanics; supercritical extraction

THEODORE T. TSOTSIS
(Ph.D., Ch.E., Illinois, Urbana, 1978) • Chemical reaction engineering; process dynamics and control

IAN A. WEBSTER
(D.Sc., Ch.E., M. I. T., 1984) *(Adjunct)* • Catalysis and reaction kinetics; transport phenomena, chemical reaction engineering; surface spectroscopy, biochemical engineering

YANIS C. YORTSOS
(Ph.D., Ch.E., Caltech, 1979) • Mathematical modeling of transport processes; flow and transport in porous media

Widener

UNIVERSITY

We take your education personally.

Master's Program in Chemical Engineering

(Including Environmental Engineering Option)

Advanced study in chemical engineering including process analysis, synthesis and design.

Core Courses . . . Thermodynamics • Transport phenomena • Reaction kinetics • Applied mathematics

Wide range of technical electives • Thesis option

Environmental engineering option provides the know-how to apply advanced chemical engineering techniques to problems in that area.

Topics include . . .

Environmental law • Advanced water and wastewater systems • Incineration/hazardous waste management

Related program in Engineering Management also available.

For more information contact:

Professor D.H.T. Chen • Assistant Dean/Graduate Programs and Research • School of Engineering • Widener University
One University Place • Chester, PA 19013-5792 • Phone 215/499-4198 • FAX 215/499-4059

THE UNIVERSITY OF BRITISH COLUMBIA

The Department of Chemical Engineering invites applications for graduate study from candidates who wish to proceed to the M.Eng., M.Eng. (Pulp & Paper), M.A.Sc., or Ph.D. degree. For the latter two degrees, Assistantships or Fellowships are available.

AREAS OF RESEARCH

Air Pollution
Biochemical Engineering
Biomedical Engineering
Biotechnology
Catalysis
Coal, Natural Gas and Oil Processing
Electrochemical Engineering
Electrokinetic and Fouling Phenomena
Fluid Dynamics
Fluidization
Heat Transfer
Kinetics
Liquid Extraction
Magnetic Effects
Mass Transfer
Modeling and Optimization
Particle Dynamics
Process Dynamics
Pulp & Paper
Rheology
Rotary Kilns
Separation Processes
Spouted Beds
Sulphur
Thermodynamics
Water Pollution

Inquiries should be addressed to:

Graduate Advisor
Department of Chemical Engineering
THE UNIVERSITY OF BRITISH COLUMBIA
Vancouver, B.C., Canada V6T 1Z4
FAX: (604) 822-6003

UNIVERSITY OF CALIFORNIA, DAVIS
Department of Chemical Engineering

Areas of Research

fluid mechanics of thin films • environmental transport
reactor design & catalysis • supercritical extraction
suspension dynamics • interfacial transport • biopolymers
polymer adhesion • transport in porous media
rheology • Langmuir-Blodgett films • process control
biomedical, biochemical & genetic engineering

Faculty

Abbott, Nicholas L.
Anderson, Herbert R., Jr.
Bell, Richard L.
Boulton, Roger
Dungan, Stephanie R.
Gates, Bruce C.
Higgins, Brian G.
Jackman, Alan P.
Katz, David F.
McCoy, Ben J.
McDonald, Karen A.
Palazoglu, Ahmet N.
Phillips, Ronald J.
Powell, Robert L.
Ryu, Dewey D.Y.
Smith, J.M.
Stroeve, Pieter
Whitaker, Stephen

For more information please write to:
Graduate Admissions Advisor
Department of Chemical Engineering
University of California
Davis, CA 95616

BIOENGINEERING AT CARNEGIE MELLON

Carnegie Mellon

Molecular Biophysics and Cellular Dynamics

transmembrane diffusion; mutagenesis and protein stability; dynamics of cytoplasmic molecules; cytoskeleton assembly; cell adhesion and motility.

Physiology and Regulation

bio-sensory perception; modeling of peripheral auditory system; metabolic networks and flux control; animal models of diabetes; xenobiotic challenges to pulmonary system.

Signal Processing/Bioinstrumentation

pattern recognition; monitoring of physiological rates; signal processing in sensory systems; three-dimensional cell imaging; fluorescent probe molecular design and applications; development of *in situ* fluorescence and NMR spectroscopy methods to investigate cells.

Biomaterials and Biomechanics

orthopedic biomechanics; bipedal locomotion; regulatory standards and testing of implantable devices; terminal of environmental hazards; surface-protein interaction.

FOR FURTHER INFORMATION, WRITE TO;

CARNEGIE MELLON UNIVERSITY
Biomedical Engineering Program
Graduate Admissions, DH 2313
Pittsburgh, PA 15213

UNIVERSITY OF DAYTON

Graduate Study in Chemical and Materials Engineering

Research assistantships (including competitive stipend and tuition) are available for students pursuing M.S. in Chemical Engineering or M.S. or Ph.D. in Materials Engineering in the following research areas:

- **PROCESS MODELING**
- **EXPERT SYSTEM PROCESS CONTROL**
- **COMBUSTION**
- **SEPARATION PROCESSES**
- **COMPOSITE MATERIALS**
- **MANUFACTURING SYSTEMS**

We specialize in offering each student an individualized program of study and research with most projects involving pertinent interaction with industrial personnel.

For further information write to:

Director of Graduate Studies
Department of Chemical and Materials Engineering
University of Dayton • 300 College Park Avenue
Dayton, Ohio 45469-0246
or call (513) 229-2627

The University of Dayton

PhD/MS in Chemical Engineering

UNIVERSITY of NEW HAMPSHIRE

Imagine an exciting education in a relaxed rural atmosphere. Imagine New Hampshire. We're located in the Seacoast region only an hour from the White Mountains to the north or from Boston to the south. Current research projects at UNH:

BIOENGINEERING
COAL PROCESSING
COMPUTER APPLICATIONS
ELECTROCHEMICAL ENGINEERING
ENVIRONMENTAL ENGINEERING
POLYMER ENGINEERING
FLAME PROCESSING
FLUIDIZATION
SOLAR ENERGY
SPACE APPLICATIONS

For information contact
Dr. SST Fan, Chairman
Department of Chemical Engineering
University of New Hampshire • Durham, NH 03824-3591

UNIVERSITY OF NORTH DAKOTA

MS and MEngr. in Chemical Engineering
Graduate Studies

PROGRAMS: Thesis and non-thesis options available for MS degree; substantial design component required for M.Engr. program. A full-time student with BSChE can complete program in 9-12 months. Students with degree in chemistry will require two calendar years to complete MS degree. A PhD program in Energy Engineering is also available to students with MS in Chemical Engineering

RESEARCH PROJECTS: Most funded research projects are energy related with the full spectrum of basic to applied projects available. Students participate in project-related thesis problems as project participants.

ENERGY AND ENVIRONMENTAL RESEARCH CENTER: A cooperative program of study/research with research projects related to low-rank coal conversion and utilization sponsored by U.S. Department of Energy and private industry is available to a limited number of students.

FOR INFORMATION WRITE TO

Dr. Thomas C. Owens, Chair
Chemical Engineering Department
University of North Dakota
Grand Forks, North Dakota 58202
(701-777-4244)

AUTHOR GUIDELINES

This guide is offered to aid authors in preparing manuscripts for Chemical Engineering Education (CEE), a quarterly journal published by the Chemical Engineering Division of the American Society for Engineering Education (ASEE).

CEE publishes papers in the broad field of chemical engineering education. Papers generally describe a course, a laboratory, a ChE department, a ChE educator, a ChE curriculum, research program, machine computation, special instructional programs, or give views and opinions on various topics of interest to the profession.

• Specific suggestions on preparing papers •

TITLE • Use specific and informative titles. They should be as brief as possible, consistent with the need for defining the subject area covered by the paper.

AUTHORSHIP • Be consistent in authorship designation. Use first name, second initial, and surname. Give complete mailing address of place where work was conducted. If current address is different, include it in a footnote on title page.

TEXT • Manuscripts of less than twelve double-spaced typewritten pages in length will be given priority over longer ones. Consult recent issues for general style. Assume your reader is not a novice in the field. Include only as much history as is needed to provide background for the particular material covered in your paper. Sectionalize the article and insert brief appropriate headings.

TABLES • Avoid tables and graphs which involve duplication or superfluous data. If you can use a graph, do not include a table. If the reader needs the table, omit the graph. Substitute a few typical results for lengthy tables when practical. Avoid computer printouts.

NOMENCLATURE • Follow nomenclature style of Chemical Abstracts; avoid trivial names. If trade names are used, define at point of first use. Trade names should carry an initial capital only, with no accompanying footnote. Use consistent units of measurement and give dimensions for all terms. Write all equations and formulas clearly, and number important equations consecutively.

ACKNOWLEDGMENT • Include in acknowledgment only such credits as are essential.

LITERATURE CITED • References should be numbered and listed on a separate sheet in the order occurring in the text.

COPY REQUIREMENTS • Send two legible copies of the typed (double-spaced) manuscript on standard letter-size paper. Clear duplicated copies are acceptable. Submit original drawings (or clear prints) of graphs and diagrams, and clear glossy prints of photographs. Prepare original drawings on tracing paper or high quality paper; use black india ink and a lettering set. Choose graph papers with blue cross-sectional lines; other colors interfere with good reproduction. Label ordinates and abscissas of graphs along the axes and outside the graph proper. Figure captions and legends may be set in type and need not be lettered on the drawings. Number all illustrations consecutively. Supply all captions and legends typed on a separate page. If drawings are mailed under separate cover, identify by name of author and title of manuscript. State in cover letter if drawings or photographs are to be returned. Authors should include brief biographical sketches and recent photographs with the manuscript.