GRADUATE EDUCATION ISSUE

• Award Lecture •
Computing in Engineering Education
From There, To Here, To Where?
Part 1. Computing
BRICE CARNAHAN

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Editor's Note to Seniors . . .

This is the 24th graduate education issue published by CEE. It is distributed to chemical engineering seniors interested in and qualified for graduate school. We include articles on graduate courses and research at various universities, along with departmental announcements on graduate programs. In order for you to obtain a broad idea of the nature of graduate work, we encourage you to read not only the articles in this issue, but also those in previous issues. A list of the papers from recent years follows. If you would like a copy of a previous fall issue, please write to CEE.

Ray W. Fahien, Editor

Fall 1990
Austin, Beronio, Taso • Biochemical Engineering Education Through Videotapes
Ramkrishna • Applied Mathematics
Rice • Dispersion Model Differential Equation for Packed Beds
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Felder • Stoichiometry Without Tears
Cohen, Tsai, Chetty • Multimedia Environmental Transport, Exposure, and Risk Assessment
Schul, Benge • ChE Summer Series at Virginia Polytechnic
Roberge • Transferring Knowledge
Coulman • ChE Curriculum, 1989
Frey • Numerical Simulation of Multicomponent Chromatography Using Spreadsheets
Fried • Polymer Science and Engineering at Cincinnati

Fall 1989
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Kummier, Mckicking, Powitz • Hazardous Waste Management
Bienkowski, et al. • Multidisciplinary Course in Biotechnology
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Randolph • Particulate Processes
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Davis • Fluid Mechanics of Suspensions
Wang • Applied Linear Algebra
Kisaalita, et al. • Crossdisciplinary Research: The Neuron-Based Chemical Sensor Project
Kyle • The Essence of Entropy
Rao • Secrets of My Success in Graduate School

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Briedis • Technical Communications for Grad Students
Deshpande • Multivariable Control Methods
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Goosen • Research: Animal Cell Culture in Microcapsules
Teja, Schaeffer • Research: Thermodynamics and Fluid Properties
Duda • Graduation: The Beginning of Your Education

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McCready, Leighton • Transport Phenomena
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Edie, Dunham • Research: Advanced Engineering Fibers
Allen, Pett • Research: Unit Operations in Microgravity
Bartusiak, Price • Process Modeling and Control
Bartholomew • Advanced Combustion Engineering

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Amundson • Research Landmarks for Chemical Engineers
Duda • Graduate Studies: The Middle Way
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Venkatasubramanian • A Course in Artificial Intelligence in Process Engineering
Moo-Young • Biochemical Engineering and Industrial Biotechnology
Babu, Sukanek • The Processing of Electronic Materials
Dayte, Smith, Williams • Characterization of Porous Materials and Powders
Blackmond • A Workshop in Graduate Education

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Graham, Jutan • Teaching Time Series
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Radovic • Coal Utilization and Conversion Processes
Shah, Hayhurst • Molecular Sieve Technology
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Woods • Surface Phenomena
Middleman • Research on Cleaning Up in San Diego
Serageldin • Research on Combustion
Wankat, Orovecz • Grad Student’s Guide to Academic Job Hunting
Bird • Book Writing and ChE Education
Thomson, Simmons • Grad Education Wins in Interstate Rivalry
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A GRADUATE COURSE IN DIGITAL COMPUTER PROCESS CONTROL

PRADEEP B. DESHPANDE AND PERUVEMBA R. KRISHNASWAMY*
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Louisville, KY 40292

Computer-based control systems have become a routine feature in the process industry. In order to be competitive, today's students must be familiar with the recent developments in control technologies which are having a significant impact on how complex industrial processes are operated. The first-listed author of this paper began offering a course in computer process control in 1975, based on the material in the literature at that time and his own perspectives. In the ensuing years, however, the course has been completely revised in light of the new and significant developments in control technology.

This paper describes what we believe to be a modern course in digital computer process control. Whenever appropriate, recent developments are highlighted, and a detailed bibliography of the textbooks and selected papers used in the course is included at the end of the article for ready reference.

Pradeep B. Deshpande is professor and a former chairman of the chemical engineering department at the University of Louisville. He has twenty years of academic and full-time industrial experience. He is the author, co-author, or editor of three textbooks and sixty papers. He consults for several companies and offers continuing education courses in several countries.

P.R. Krishnaswamy received his BSc degree from Banaras Hindu University (India) and his PhD degree from the University of New Brunswick. His teaching and research interests include process dynamics, process control, separation operations, and fluidization. He has recently shared experiences in control research during a sabbatical at the University of Louisville and Purdue University.

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The goals of the course are to learn how to design, analyze, and implement direct-digital control systems for single-loop and multivariable systems.

THE REVISED COURSE

An outline of the revised course is shown in Table 1. For convenience, the course is divided into three parts: Part 1 is devoted to introductory concepts and the development of a mathematical background; Part 2 covers the analysis and design concepts of SISO digital control systems; and Part 3 is concerned with advanced control concepts.

PART 1
Introductory Concepts and Mathematical Background

The course begins with an introduction to digital computer control. The essential features of conventional control based on continuous or analog signals and of digital control, which encompasses hybrid (discrete/analog) signals, are outlined. The meanings of direct-digital control (DDC), supervisory control, and distributed control are explained.

Much of the material in the course deals with DDC concepts, and as a lead-in to the next series of topics, the elements of a single-loop DDC system are examined. We point out that the DDC-loop consists of the usual elements of any control system—namely, the process, a measurement-device transmitter, and a final control element. In addition, a DDC system has an analog-to-digital (A/D) converter that samples measured process outputs at a sampling frequency selected by a real-time programmable clock, a digital computer or digital controller, and a digital-to-analog (D/A) converter that converts computer-generated discrete control commands into continuous signals for operating the final control elements.

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Chemical Engineering Education
The goals of the course are to learn how to design, analyze, and implement direct-digital control systems for single-loop and multivariable systems. It should be emphasized that the availability of control computers allows the designer to implement control methodologies that are either impractical or impossible with conventional control hardware. Examples include dead-time compensation, feedforward control, synthesized digital control algorithms, and model predictive control.

The sequence of lectures is devoted to the study of each element of the DDC loop. The first among them is concerned with computer-control hardware and software. The hardware description includes the central processing unit, the main memory/bulk memory, the computer input/output (I/O) devices, process I/O, the A/D and D/A converters, and a real-time programmable clock. The software concepts include an introduction to assembly-level programming, real-time Fortran, and Basic. At the University of Louisville a PDP 11/03-system has served our control-computing needs for the last several years. The Fortran callable subroutines for A/D, D/A, and the real-time clock for this machine are used to explain how the real-time commands are embedded into a Fortran control program.

The next topic deals with single-loop PID control. In typical industrial situations, fast loops (flow loops) operate under digital PID-type control algorithms. In these lectures the instructor derives the digital PID algorithm from conventional controller equations that the students are familiar with and points out the role of the sampling period in stability and performance. At the end of the lectures the students develop a computer program and implement digital PID control on a four-loop laboratory process. (Note that doing this work does not require a background in z-transforms.) Being able to operate a process under the control of a digital computer after only three weeks of the semester has been an exciting experience for the students.

The next topics to be covered are mathematical representation of an AID converter, study of z-transforms, derivation of a pulse-transfer function, and the zero order hold transfer function. Then open-loop and closed-loop pulse transfer functions are derived, and open-loop and closed-loop responses are evaluated by hand and the answers verified by CAI (Computer-Aided Instruction) software that has only recently been developed. Information on this CAI-control software can be found in the references at the end of this article.

### TABLE 1

<table>
<thead>
<tr>
<th>Topic</th>
<th>Time Devoted (50-min. periods)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PART 1: Introductory Concepts and Mathematical Background</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Introduction to computer process control</td>
<td>1</td>
<td>7, 21, 23</td>
</tr>
<tr>
<td>2. Computer-control hardware and software</td>
<td>3</td>
<td>7, 9, 20</td>
</tr>
<tr>
<td>3. How to implement PID controllers with digital computers</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>4. Mathematical representation of A/D converter</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>5. Z-transforms</td>
<td>4</td>
<td>7, 12, 21, 23</td>
</tr>
<tr>
<td>6. Transfer function of D/A converter</td>
<td>1</td>
<td>7, 25</td>
</tr>
<tr>
<td>7. Pulse transfer functions</td>
<td>1</td>
<td>25, 11, 7</td>
</tr>
<tr>
<td><strong>PART 2: Analysis and Design of Digital Control Systems</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Design of digital-control algorithms; deadbeat-control Dahlin algorithm; internal-model control (factorization method); Smith predictor; simplified-model predictive control; conservative-model based control; PID control</td>
<td>6</td>
<td>7, 8, 12, 26, 37, 21</td>
</tr>
<tr>
<td>10. Stability of sampled-data control systems</td>
<td>1</td>
<td>7, 25</td>
</tr>
<tr>
<td><strong>PART 3: Advanced Control Concepts</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11. Process identification; step testing; pulse testing; dynamic matrix identification; introduction to time-series analysis</td>
<td>5</td>
<td>12, 7, 6, 36</td>
</tr>
<tr>
<td>12. Practical nonlinear control</td>
<td>2</td>
<td>32, 50, 30, 31</td>
</tr>
<tr>
<td>13. Adaptive control and self-tuning; auto-tuning; gain scheduling; model reference adaptive control; self-tuning regulators</td>
<td>2</td>
<td>28, 2, 59, 61, 7</td>
</tr>
<tr>
<td>14. Feedforward control</td>
<td>1</td>
<td>7, 12, 21</td>
</tr>
<tr>
<td>15. Cascade control</td>
<td>2</td>
<td>7, 12</td>
</tr>
<tr>
<td>16. Multivariable control</td>
<td>7</td>
<td>7, 8, 12, 46, 53, 17, 18, 40, 41</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>42</td>
<td>periods: one semester or equivalent</td>
</tr>
</tbody>
</table>

The discussion of pulse-transfer functions and open-loop responses leads us into an exciting topic—the notion of an impulse response (IR) model, which enables us to predict the process output at the next sampling instant from past inputs through use of the equation

\[
Y_{K+1} = \sum_{i=1}^{N} h_i u_{K+1-i}
\]
Beginning with the definition of the pulse-transfer function, \( G(z) = Y(z)/U(z) \), the instructor can easily derive Eq. (1), as shown for example in Deshpande and Ash.\(^{19}\) IR-type models have distinct advantages: they can be derived from easily-available step response data; the response curve need not be fitted to a structured model and the order of the process is not important; and the use of an IR-type model considerably simplifies the evaluation of closed-loop responses by computer simulations.

The next topic is the design of digital-control algorithms for SISO (Single-Input Single-Output) systems. While controllers can be designed by a number of methods, we believe that the direct-synthesis method is best suited for this course. The basic idea is to solve the closed-loop pulse-transfer-function equation for the controller, giving

\[
D = \frac{\frac{Y}{R} - \frac{1}{G}}{1 - \frac{Y}{R}}
\]

(2)

The closed-loop response is specified according to the equation

\[
\frac{Y}{R} = FG
\]

(3)

By selecting the desired expressions for \( F \), several well-known control algorithms can be obtained; for example, the choice of \( F = 1 \) gives deadbeat control. Through use of the CAI software, students quickly learn that deadbeat control can give rise to rippling behavior of the controller output. Furthermore, deadbeat controllers are very sensitive to modeling errors.

The choice of a first-order lag for \( F \) gives a Dahlin algorithm. The instructor can easily show that a Dahlin algorithm is the same as an internal-model-control (IMC) algorithm if a first-order filter is employed in the latter. It would also be helpful to derive the IMC structure from the sampled-data control structure and show that the two representations are equivalent. Once the IMC structure is derived, one can go over the stability theorems and design IMC controllers for a variety of processes—including those that exhibit dead-time and inverse response.

In the discussion of IMC, the instructor can derive the Smith Predictor algorithm and point out the similarities between the two approaches. Also, through simulation exercises, the instructor can show that the latter does not tolerate modeling errors well and that the tuning of the Smith Predictor-based PID controllers becomes difficult in the presence of modeling errors.

At one end of the spectrum of control equality there is a notion of perfect control (deadbeat control). IMC is an algorithm that delivers perfect control in the absence of modeling errors. In the presence of modeling errors, however, the designer must back away from the notion of perfect control in favor of robustness, by choosing an appropriate filter.

At the other end of the spectrum of control quality there is the notion of open-loop control. Simplified model-predictive control (SMPC) and conservative model-based control (CMBC) are algorithms which assume that at worst the controller should be able to provide a set-point response that is as good as the open-loop response. These algorithms are derived as follows: the open-loop behavior of an open-loop stable process is given by

\[
\frac{Y}{R} = \frac{G}{K_p}
\]

(4)

Substituting for \( Y/R \) from Eq. (4) into Eq. (2) gives

\[
D = \frac{M}{E} = \frac{1}{K_p - G}
\]

(5)

The choice of Eq. (5) for the controller will deliver a set-point response that is the same as the normalized open-loop response. The response can be speeded up by introducing a tuning-constant \( \alpha \), giving the SMPC algorithm

\[
D = \frac{\alpha K_p}{K_p - G}
\]

(6)

SMPC features a single-tuning constant that can be found by offline optimization. Dead-time compensation can be incorporated by modifying Eq. (5) according to

\[
D = \frac{A}{K_p - AG}
\]

(7)

where

\[
A = \frac{1 - \beta^{-1}}{1 - \beta}
\]

(8)

Equation (7) represents the CMBC control law. CMBC also features a single-tuning constant \( \beta \) whose value can be found by offline simulation.

In the discussion of various control algorithms, the students are reminded that the algorithms which give the best servo responses are not necessarily the ones that are best for regulatory control. Furthermore, the design work assumes that the processes are linear, but in reality they are not. Consequently, the algorithms that give the best performance in simulation work may not be the best when they are implemented on real-life nonlinear processes.

The next topic of discussion is stability. Stability concepts relating to sampled-data systems can be effectively derived by utilizing the relationship be-
between the Laplace transform operator $s$ and the $z$-transform operator $z$. The discussion of stability concludes with a method for finding the roots of the characteristic equation in the $z$-domain.

**PART 3**

**Advanced Control Concepts**

The next topic is process identification. The traditional methods which we cover are step testing, pulse testing, and fitting of models to frequency-response plots. An ideal method should identify process dynamics from a test that does not force the process away from the steady-state operating condition. One such method that meets these needs is the relay method in which a relay perturbs the process and the resulting process output/input data provide the ultimate frequency and ultimate gain of the system. These data lead to optimized tuning constants of a PID-type controller.

Another method, called dynamic matrix identification, calls for perturbing the process by a series of up-and-down step changes in the input $U(z)$ around the steady state, given by the equation

$$U(z) = U_0 + U_1 z^{-1} + U_2 z^{-2} + U_3 z^{-3}$$

Then, in the light of the impulse response model

$$Y(z) = \sum_{i=1}^{N} h_i z^{-i}$$

the output is given by

$$Y(z) = 0 + h_1 U_0 z^{-1} + (h_2 U_0 + h_1 U_1) z^{-2} + ...$$

Equations (11a) and (11b) show that the impulse response coefficients can be computed from the experimental input and output data.

The last method covered which is suited to use in a noisy environment is time-series analysis. In this method the process is described in two parts: one accounts for the model and the other is a noise term that accommodates the effect of unmeasured load disturbances. A PRBS (pseudo random binary sequence) signal is applied to the process and the analysis of the input-output data gives the model. Time constraints prevent an in-depth treatment of the theory, but the software available (e.g., Matlab; see also Reference 21) can be effectively used to illustrate the method.

The next topic is practical nonlinear control. The treatment is restricted to a conceptually simple practical method which appears to have considerable potential. It is well known that the closed-loop response of many complex nonlinear SISO systems can be described by a linear second-order transfer function, given by

$$\frac{Y(s)}{R(s)} = \frac{\eta_1 s + \eta_2}{s^2 + \eta_1 s + \eta_2}$$

or, in the time domain

$$\frac{dY}{dt} = \eta_1 E + \eta_2 \int E \, dt$$

where $E = R - Y$.

The terms $\eta_1$ and $\eta_2$ determine the shape of the response. Now, the nonlinear process is described by a nonlinear differential equation of the form

$$\frac{dY}{dt} = f(Y^n, \ell n Y, e^{AY}, \text{etc.}) + U$$

Equating Eqs. (13) and (14) gives the nonlinear control law

$$U = -f(Y^n, \ell n Y, e^{AY}, \text{etc.}) + \eta_1 E + \eta_2 \int E \, dt$$

If the resulting control law turns out to have undesirable properties, such as ringing or constraint violations, then a minimization problem based on the difference between actual and the desired values of the derivative $dY/dt$ is solved to derive the control law. Note that this analysis of nonlinear control is based on continuous-time systems. The system equations would have to be discretized for use in a digital-computer-based control system.

The next set of topics falls into the category of what is commonly referred to as advanced control concepts. The first topic to be covered is adaptive control and self-tuning. Time limitations permit only a brief introduction. The need for adaptive control arises due to changing process characteristics. Auto-tuning, gain scheduling, self-tuning regulators, and model-reference adaptive control are examples to be covered. The use of a relay to identify the ultimate gain and ultimate period of a proportional controller in auto-tuning has already been mentioned.

Feedforward and cascade control are the next topics to be covered. Feedforward control is meant to improve the response of feedback control systems in the presence of disturbances in process loads, while cascade control is meant to arrest the detrimental effect of disturbances in the manipulated variable.

The final topic to be covered deals with multivariable control, which includes the topics of interaction analysis and variable pairing, multiloop control for modestly-interacting systems (including PID control) -179
controllers designed by the biggest log modulus tuning method), multiloop IMC and CMBC/SMPC controllers, explicit decoupling in conjunction with PID controllers, reference systems decoupling, and multivariable model predictive control. Model predictive control includes dynamic matrix control, model algorithmic control, and predictive IMC.

Model predictive control techniques utilize stepor impulse-response models of the process. These models are used in conjunction with optimization techniques to calculate controller outputs. It should be emphasized that complex multivariable processes must invariably be operated in the vicinity of constraints. Therefore, students must have familiarity with some methods, such as linear and quadratic programming for solving constrained multivariable optimization problems and how they are used in conjunction with model predictive control. Simulation examples can be used to illustrate the concepts.

This concludes the course. The first-listed author offers the course regularly at the University of Louisville and as an intensive short course for industry in the U.S., Europe, Kuwait, and India. The reactions of the participants have always been favorable.

**NOMENCLATURE**

- **D** = digital controller
- **E** = error
- **F** = filter
- \( G_\mu \) = model transfer function
- **h** = impulse response coefficient
- **i** = sampling instant
- **K_p** = process steady-state gain
- **M** = controller output
- **N** = number of sampling periods in open-loop settling time
- **R** = set-point
- **s** = Laplace transform operator
- **t** = time
- **U** = process input
- **Y** = process output
- **z** = transform operator

**Greek**

- \( \eta_1, \eta_2 \) = PID-type tuning constants
- \( \alpha, \beta \) = tuning constants

**REFERENCES**

**Books**


**Journal Articles**


THE ACADEMIC ELITE IN CHE

Dear Editor:

A ranking of the most highly regarded doctoral programs in chemical engineering was presented in the November 1983 edition of Changing Times. This ranking was based on a study published by the National Academy of Sciences. For the ranking reported by Changing Times two key measures of reputation from the National Academy study were combined: 1) "faculty quality" assessed how chemical engineering professors around the country rated their peers in the same discipline, and 2) "program quality" assessed how well the faculty thought each program educated research scholars and scientists.

Changing Times combined these two measures and derived a ranking of the top ten percent of the programs in chemical engineering. If one goes by the assumptions of the Changing Times article, the eight schools with the highest combined scores represented the "academic elite" in chemical engineering—the "best" programs in the country.

Given the subjective nature of the evaluation process which produced the National Academy rankings, I decided to examine the composition of the faculties of the top eight schools. I suspected that these departments would be substantially linked to one another through the hiring of one another's graduates, hence enhancing one another's reputations. I also expected that among the academic elite there would be a high degree of academic "inbreeding"—the hiring of graduates from one's own program.

I used the American Chemical Society Directory of Graduate Research 1989 to examine the full-time faculties of the eight highest-ranked chemical engineering departments. An item of primary interest was where the full-time faculty members at these institutions had received their doctoral degrees. It
soon became obvious that there were numerous interrelationships among the departments in terms of where the faculty had received their doctoral degrees.

The following table lists the top-ranked departments and indicates the percentages of full-time faculty who received their doctoral degrees from one of the "elite" departments on the list (which includes those who received their degrees from the same departments where they are currently on the faculty).

<table>
<thead>
<tr>
<th>Rank</th>
<th>Program</th>
<th>N</th>
<th>Percentage</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Elite 1</td>
<td>Own 2</td>
</tr>
<tr>
<td>1</td>
<td>Minnesota</td>
<td>32</td>
<td>50.0</td>
<td>0.0</td>
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<td>2</td>
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<td>20</td>
<td>65.0</td>
<td>15.0</td>
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<td>3</td>
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<td>21</td>
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<td>3</td>
<td>Caltech</td>
<td>8</td>
<td>75.0</td>
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<td>Stanford</td>
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<td>69.7</td>
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<td>TOTALS</td>
<td>153</td>
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</table>

1 Percentage of faculty who received PhDs from one of the eight top-ranked programs.
2 Percentage of faculty who received PhDs from the program in which they are now employed.
3 Number of PhD recipients from the programs who were on the faculty of one of the top-ranked programs in 1988.

As can be seen in the table, in all of the top-ranked departments a substantial proportion of the faculty received PhDs from one of the "academic elite." The California Institute of Technology and the University of Illinois had the highest percentages of degree holders from the top-ranked departments (75.0%), and the University of Minnesota had the lowest (50.0%). At most of the schools, anywhere from one-half to three-quarters of the faculty graduated from one of the prestigious programs.

The table also addresses academic inbreeding among the top-ranked chemical engineering programs. Berelson and Caplow and McGee have demonstrated that a high degree of inbreeding among elite schools is not accidental. According to both studies, if elite programs are to maintain their prestige, they cannot hire a large number of PhDs from lower-ranked departments, and this would include PhDs from upwardly mobile "middlemen" programs where elite credentials have yet to be established. In his study of sociology departments, Gross found that the higher the prestige of a department, the greater the proportion of "home-grown" graduate faculty. With some modifications, Shichor's study confirmed Gross' findings. Shichor found the relationship between departmental inbreeding and the prestige of a department to be curvilinear, with the highest and lowest ranking departments having the highest rates of inbreeding while mid-level departments were found to have the lowest rates.

As can be seen from the table, in 1989 the school with the largest percentage of its own graduates on its full-time chemical engineering faculty was Massachusetts Institute of Technology (42.4%). The University of Minnesota, California Institute of Technology, and the University of Illinois had not hired any of their own graduates.

The table also presents the number of PhDs produced from each department who were full-time faculty members of one of the elite departments in 1989. MIT had thirty-one of its graduates in faculty positions at the elite departments, and Berkeley was next with seventeen. Illinois had the least with four.

I think that graduate departments in chemical engineering (or in any discipline) must rely to a large extent upon their reputations in order to attract highly qualified faculty and graduate students to participate in their programs. The eight chemical engineering graduate programs that were top-ranked in the 1981 National Academy study are undoubtedly strong programs. I certainly do not wish to argue that they are not. However, the data suggest that a number of subjective factors influence the procedure by which academic departments are ranked. Primarily, I contend that a rather small group of institutions (eight in this instance) tend, consciously or unconsciously, to enhance one another's reputations by hiring one another's graduates.

The Changing Times article used two measures of reputation in order to establish its list of the "best" graduate departments: how professors rated their peers in the same discipline, and how well the faculty thought each program educated research scholars and scientists. These criteria are vitally linked; when elite faculty are asked to rate their peers at other schools, they are (to a large extent) rating their former professors or students. There are a total of 153 full-time faculty in the chemical engineering elite, and 97 of them (63.4%) graduated from one of these distinguished programs. Clearly, it is in their best interest to rank their alma maters highly.

The remarkable stability in the ranking of elite programs over the last few decades suggests that not only do elite faculty rate their own programs highly, but so also do large numbers of faculty from...
less prestigious programs. Several factors may explain this phenomenon. On the one hand, the data suggest that the consistently high rankings of elite programs are due to the large number of graduates that those very same programs put into the discipline each year. While they place some graduates in other elite schools, most descend into mid-level schools or less renowned institutions where they continue to subjectively rank their alma maters as the very best. The high number of elite school graduates at all levels also seems to enable them to play a disproportionate role in shaping opinion within the discipline.

There is another way of explaining the relative stability in the ranking of elite programs over time. Obviously, there are not enough faculty from elite schools at middle and lower level programs for them to maintain the high ranking of their alma maters without some support from their non-elite colleagues. Tradition may be a partial explanation for the non-elite's acceptance of their inferior status. Elite schools have been accorded high esteem for decades, and these traditions typically have gone unchallenged.

A more likely explanation, however, is that the non-elite, in a classic example of Marxian false consciousness, have adopted their elite peers' assessment that the latters' programs and faculties are superior. Buttressed by only a few subjective government surveys and contact with a handful of individuals from elite programs, the non-elite have not only accepted but also even promoted the notion that elite graduate programs are deserving of high esteem, whereas others, including their own, are not.

Ultimately, I think it should be asked: Are the eight highest-ranked programs indeed the best PhD programs in chemical engineering, or do they comprise an "academic elite" with a large number of faculty members in the discipline and an obvious interest in perpetuating the present ranking system? I believe that data suggest that the latter is true.

Two final comments seem in order. First, I contend that because of their subjectivity, current ranking systems are a detriment to the discipline. They may impede professional mobility, reward status over achievement, and result in programs of lesser renown being bypassed, even though they may merit as high or higher recognition than do those of the elite. Second, I believe that current, subjective ranking systems incorporate serious distortions and misrepresentations. Because they have the potential to do as much harm as good, I recommend that as they are presently constituted, subjective systems of departmental ranking should be routinely ignored.

**Jeffrey H. Bair**

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**ChE book review**

**CHEMICAL AND ENGINEERING THERMODYNAMICS**

**Second Edition**


**Reviewed by**

J.P. O'Connell, D.J. Kirwan

University of Virginia

This is the second edition of a text for undergraduate chemical engineers. As the author's preface points out, the objectives of both editions are the same: 1) to develop a course relevant to other parts of the curriculum, such as separations, reactors, and design, and 2) to present sufficient detail in a way that leads to good understanding and proficiency of application.

Distinctive treatments of the first edition included introduction of the mass, first, and second law balance equations in the same way (this may demystify entropy for some students). Also, treatment of the variety of phase equilibrium situations among solids, liquids, and vapors is more complete and more categorized than in other texts.

The major change from the first edition is the inclusion of BASIC programs for calculating 1) thermodynamic properties and VLE for pure and for multicomponent systems from a cubic EOS, 2) low-pressure VLE from activity coefficients from group contributions, and 3) equilibrium constants and stan...Continued on page 195.
The first textbook to present catalysis in a coherent, unified manner!

**CATALYTIC CHEMISTRY**

Bruce C. Gates, University of Delaware
51761-5, 432 pp., 1992

Gathering catalysis material from the fields of chemical reaction engineering, chemical engineering, kinetics, organometallic chemistry, and physical chemistry, this unique text presents the first unified, easy-to-teach treatment of catalytic chemistry. This exciting new text:

- Demonstrates to students that the fragments to which they have been exposed in other courses constitute a large, important, challenging and opportunity-rich subject.
- Includes an outline of the subject with examples, problems and solutions. Instructors can emphasize and build on specific subject areas.
- Is full of practical knowledge and can be used by both scientists and engineers working in the discipline, including researchers and industry experts.

A Solutions Manual (54588-0) with Answers and Solutions to most problems is available upon adoption.

**Other Titles of Interest**

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  Robert W. Fox, Purdue University
  Alan T. McDonald, Purdue University
  54852-9, 704 pp., 1992

- **Chemical Reactor Analysis & Design, Second Edition**
  G. F. Froment, Rijks Universiteit—Gent, Belgium
  Kenneth Bischoff, University of Delaware
  51044-0, 733 pp., 1990

  61246-4, 992 pp., 1990

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  David P. Incropera, Purdue University
  61247-2, 896 pp., 1990

- **Process Dynamics & Control**
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  Thomas F. Edgar, University of Texas, Austin
  Duncan A. Mellichamp, University of California, Santa Barbara
  86389-0, 714 pp., 1989

- **Computer Applications for Engineers**
  Thomas K. Jewell, Union College
  60117-9, 800 pp., 1991

**Other Best Sellers...**

- **Fundamentals of Fluid Mechanics**
  Munson/Young/Okiishi,
  85526-X, 843 pp., 1990

  87324-1, 668 pp., 1986

- **Chemical and Engineering Thermodynamics, Second Edition with Disk, Sandler**
  83050-X, 622 pp., 1989

- **Fundamentals of Engineering Thermodynamics**
  Moran/Shapiro,
  89576-8, 707 pp., 1988

- **Fundamentals of Classical Thermodynamics, Third Edition, English/Sl Version**
  Van Wylen/Sonntag,
  86173-1, 749 pp., 1986

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TWENTY-NINTH ANNUAL LECTURESHP AWARD TO DARSH WASAN

The 1991 ASEE Chemical Engineering Division Lecturer is Darsh Wasan of the Illinois Institute of Technology. The purpose of this award is to recognize and encourage outstanding achievement in an important field of fundamental chemical engineering theory or practice. The 3M Company provides the financial support for this award.

Bestowed annually upon a distinguished engineering educator who delivers the annual lecture of the Chemical Engineering Division, the award consists of $1,000 and an engraved certificate. These were presented to Dr. Wasan at the banquet during the ASEE annual meeting in New Orleans, Louisiana, on June 8, 1991.

Dr. Wasan's lecture was entitled "Interfacial Transport Processes and Rheology." It will be published in a forthcoming issue of CEE.

The award is made on an annual basis, with nominations being received through February 1, 1992. Your nominations for the 1992 lectureship are invited.

AWARD WINNERS

George Burnet (Iowa State University) was the recipient of the highest Society award for service to education in engineering, engineering technology, and allied fields, the W. Leighton Collins Award. It is given for highly significant individual contributions to the profession.

The Senior Research Award was presented to Robert S. Schechter (The University of Texas at Austin). This award recognizes and honors individuals who have made significant contributions to engineering research.

The sixth annual Corcoran Award, recognizing the most outstanding paper published in CEE in 1990, was presented to coauthors John M. Prausnitz and Davor P. Sutija (University of California, Berkeley) for their article "Chemical Engineering in the Spectrum of Knowledge."

The Joseph H. Martin Award was presented to Richard C. Bailie (West Virginia University) for the best paper presented at the annual ASEE meeting.

The division presented its DELOS Distinguished Service Award to Klaus D. Timmerhaus (University of Colorado) in recognition of his many contributions to the profession.

Peter K. Kilpatrick (North Carolina State University) received an AT&T Foundation Award which recognizes and honors outstanding teachers of engineering students, while Anthony N. Beris (University of Delaware) and Jeffrey A. Hubbell (The University of Texas at Austin) both were recognized as Dow Outstanding Young Faculty.

NEW PUBLICATIONS BOARD MEMBERS

The Publications Board of CEE has been reorganized and now includes the following members in addition to its Chairman E. Dendy Sloan, and its Past Chairmen, Gary Poehlein and Klaus Timmerhaus: George Burnet (Iowa State University), Anthony T. DiBenedetto (University of Connecticut), Thomas F. Edgar (University of Texas at Austin), Richard M. Felder (North Carolina State University), Bruce A. Finlayson (University of Washington), H. Scott Fogler (University of Michigan), J. David Hellums (Rice University), Carol M. McConica (Colorado State University), Angelo J. Perna (NJIT), Stanley I. Sandler (University of Delaware), Richard C. Seagrave (Iowa State University), M. Sami Selim (Colorado School of Mines), James E. Stice (University of Texas at Austin), Phillip C. Wankat (Purdue University), and Donald R. Woods (McMaster University).

NEW DIVISION OFFICERS

The Chemical Engineering Division officers for the 1991-1992 term include: Past Chairman, Tom Hanley; Chairman, Timothy J. Anderson; Secretary-Treasurer, William L. Conger. (Chairman-Elect and Directors had not been named at the time this issue of CEE went to press.)
CHEMICAL KINETICS, FLUID MECHANICS,
AND HEAT TRANSFER IN THE FAST LANE

The Unexpurgated Story of a Long-Range Program of
Research in Combustion

STUART W. CHURCHILL
The University of Pennsylvania
Philadelphia, PA 19104-6393

The presentation of experimental and theoretical
findings in a journal usually implies that the
path of the investigation of which they are the culmi­
nation was well-planned and straightforward.
Such is rarely the case, however, particularly with
exploratory research for which unanticipated results
are the justification and the reward. Indeed, the
most useful results are often the consequence of a
deviation from the original objective in order to ex­
plain, resolve, or explore an apparent anomaly. Most
discoveries and innovations so arise.

This paper utilizes the history of a long-term (40-
year) investigation of combustion inside tubes to
illustrate the true, unvarnished path of explorato­
ry research with all of its turnings, windfalls, misdirec­
tions, triumphs, and disasters. The primary objec­
tive of this recounting is to persuade doctoral stu­
dents (and perhaps their advisors) that the anoma­
lies observed in experiments or in comparing experi­
ments and theoretical solutions are not to be ig­
nored, hidden, or deplored, but rather should be
taken as a signal of possibly important unknown be­
havior that may actually justify a diversion in, an­
addition to, or even a complete redirection of the
research. A second, related objective is to dem­
onstrate the helpful (and indeed, essential) role of theo­
retical modeling in explaining experimental results
and, particularly, anomalies.

ACOUSTICALLY RESONANT COMBUSTION

The research program that supported me as a
graduate student involved the ignition of solid prop­
ellants by a stream of gas at high temperature. We
rationalized that a mixture of $\text{O}_2$ and inert gases was
equivalent in that respect to the products of combus­
tion of a primer. My curiosity was provoked and
unsatisfied as to the possible effects of combustion
itself on heat transfer, and sometime thereafter I
persuaded Donald W. Sundstrom to investigate this
subject for his doctoral research. Supported equip­
ment-wise by an unrestricted grant from the Esso
Engineering and Research Company, we chose a
geometry unrelated to the ignition of propellants but
of more general interest—namely heat transfer from
a flame of premixed air and propane stabilized on a
central bluff body inside a 25.4-mm-ID stainless­
steel tube. The choice of combustion inside a tube,
which was arbitrary on our part and at that time
relatively unexplored, proved to be serendipitous not
only in terms of the immediate results, but also in
precursing the entire subsequent chain of events
described herein.

Although acoustic resonance was not anticipated
to be a significant factor, Sundstrom observed a cor­
relation between the local rate of heat transfer and the
aurally-sensed amplitude of the noise generated
by the flame, and he promptly acquired the appro­
priate instrumentation for characterization of the
latter. The local rate of heat transfer was found to
depend primarily on the pattern of flow generated
by the combustion, but that pattern was found in
turn to be influenced strongly by the flame-gener­
at ed acoustics.[1] The latter were rationalized to be initi­
ated by the periodic shedding and combustion of the
vortices generated by the flameholder, and to be
enhanced by the resulting resonant oscillations in
pressure. Theoretical calculations indicated that the
frequency of the oscillations corresponded to the lon­
A study of the literature on flame-generated oscillations suggested that the "screeching" combustion associated with jet engines might have a similar cause, but be due to tangential rather than longitudinal oscillations. Sundstrom was unable to produce screeching combustion in his apparatus.

A study of the literature on flame-generated oscillations suggested that the "screeching" combustion associated with jet engines might have a similar cause, but be due to tangential rather than longitudinal oscillations. Sundstrom was unable to produce screeching combustion in his apparatus, but William N. Zartman, the following student, determined from crude, preliminary experiments with a flame stabilized on a bluff body inside plain, uninstrumented and uncooled pipes of various sizes, that screeching combustion could be made to occur for pipe diameters greater than 100 mm. Hence, stainless-steel pipe with a diameter of 127 mm was chosen for his doctoral research. Amplitudes of as great as 160 db at a frequency of 4125 Hz were attained.

The research itself documented a linear increase in the local heat-transfer coefficient within the tube with the amplitude of the resonant oscillations, and indicated that these oscillations could be dampened by the installation of 1/4-wavelength tubes radially at the theoretically-identified nodes. The work of Zartman was distinguished in character by his use of inexpensive and brief preliminary experiments to choose the conditions for detailed study and by the use of theoretical analysis not only to explain but also to develop a method for controlling the experimentally-observed behavior.

A PRELIMINARY MODEL FOR THERMALLY STABILIZED COMBUSTION

In order to eliminate the source of the acoustic resonance, rather than just dampen it, I speculated on the possibility of stabilization without backmixing. I thereupon persuaded two students to attempt to model (as a term project in a seminar-type course) the stabilization of a flame inside a ceramic channel by thermal feedback only. One of them, Ward O. Winer, concluded from a very idealized model based on the postulates of plug flow with perfect radial mixing, an infinite rate of combustion following the attainment of an arbitrary temperature of ignition, and a tube of infinite length with an emissivity of unity and a negligible conductivity, that a flame could be stabilized within the channel by wall-to-wall radiation only.

THERMAL STABILIZATION IN A CERAMIC TUBE

The promising (if somewhat hypothetical) result of Winer gave me the courage to persuade Thomas D. Bath to undertake experimental research on radiative stabilization in a ceramic tube for his doctorate. Bath succeeded in establishing a flame from premixed propane vapor and air inside a 25.4-mm ceramic tube, but (as contrasted with the experiments of Sundstrom and Zartman) the temperature of the wall approached that of the flame. As a consequence, every tube cracked during the process of startup, raising the spectre that the stabilization might be due to recirculation downstream from the crack. We were disappointed that the flame fluctuated and was somewhat noisy, but concluded this behavior might also be attributable to the cracks. Because of the poor definition of the conditions inside the tube, we chose not to publish these results in the archival literature.

THERMAL STABILIZATION IN A CERAMIC BLOCK

As a consequence of such a discouraging experience, I might not have resumed research on thermally-stabilized combustion at the University of Pennsylvania (where I had now relocated) had I not discovered, as a consultant to the Marathon Oil Company, that the ceramic Wulff furnace elements used by them for the thermal cracking of methane would withstand (because of their considerable porosity) temperatures and temperature gradients as high as those encountered in the experiments of Bath. Marathon graciously donated several elements for our research. These consisted of 254-mm-long blocks perforated by round 9.52-mm holes in a triangular array. Cementing three such elements together produced a burner with seven channels. The central one was used for the measurements, and the outer six functioned as guard heaters.

With this promising device in hand, I persuaded Joseph L.-P. Chen to undertake as his doctoral research a continuation of the work begun by Bath. Considerable patience and ingenuity were required to establish a stationary flame in this ceramic block the first time; without the confidence generated by
the idealized theoretical solution of Winer and the experiments of Bath with tubes, we might not have persisted through the many failures. Once we learned how, establishing a stationary flame became routine (if time-consuming), and Chen determined by tedious trial and error the limits of flow for a stable flame of premixed propane and air within the block. For all of these conditions, the process of combustion was noticeably clean, quiet, and non-fluctuating as compared to conventional processes, all of which involve backmixing—by diffusion in laminar flames, by recirculation in bluff-body-stabilized flames, and by turbulent fluctuations in jet-mixed flames.

Following this phase of the work, Chen decided to investigate the dependence of the range of stable flames on the diameter of the channels by cementing in ceramic liners with an ID of 4.76 mm. Although combustion could be established in these smaller channels, the flame was (to our surprise and disappointment) diffuse and oscillatory. This difference in behavior was clearly associated with the regime of flow upstream from the flamefront, being laminar in the 4.76-mm channels and barely turbulent in the 9.52-mm ones.

In retrospect we were lucky. If the original channels in the Wulff furnace elements had been 8 mm or less in diameter, we might have abandoned this line of research as uninteresting owing to the relatively poor combustion which occurs in the laminar regime. Instead, because of the clean-cut behavior observed in the 9.52-mm channels, we realized that we had discovered a new and promising process of combustion. Even so, we did not yet even begin to appreciate all of its unique characteristics.

MODELING OF THERMALLY STABILIZED COMBUSTION

Despite the above-mentioned accomplishments, I was somewhat critical of Chen because of his failure to attain a high degree of reproducibility for his data (which is an essential requirement of good experimental work), particularly in the determinations of the location of the flamefront for various conditions. I was also somewhat impatient with his failure to produce a numerical solution for an extended theoretical model. Both of these judgements proved to be quite unfair. As shown by later work, the irreproducibility was inherent in the process. As regards the numerical solution, the model involved an integro-differential equation with split boundary conditions for the temperature in the solid phase, together with differential equations for the temperature and composition in the gaseous phase, and was truly formidable at that stage of development of numerical methods.

Despite no previous experience with either computers or numerical methods, Chen eventually did devise an ingenious and successful procedure that produced a solution in close accord with his experimental results. The model incorporated a number of idealizations including global kinetics, plug flow, and perfect radial mixing, but only one significant empiricism—the effective energy of activation, which he chose to force agreement with respect to location of the computed and measured longitudinal profiles in temperature in the ceramic block.

One disturbing aspect of the numerical procedure was the dependence of this effective energy of activation on grid size. Even more startling was the prediction of six additional stable solutions for the same external conditions. Three of these multiple states were closely grouped upstream and four downstream in the tube. We speculated in print that two of the seven solutions, i.e., one from each grouping, might have physical validity by analogy to those for a perfectly mixed exothermic reactor, but that the other five were probably artifacts of the approximate and iterative method of solution—a not uncommon experience with integral equations.

The numerical solution revealed that the temperature of the burned gas just beyond the flamefront exceeded the adiabatic flame temperature. This result, which is perhaps startling at first glance, is not a violation of the second law of thermodynamics but simply a consequence of the refluxing of energy backward across the flamefront by wall-to-wall radiation and in-wall conduction. The temperature of the burned gas leaving the burner is of course below the adiabatic value by an amount equivalent to the total heat losses from the ceramic block to the surroundings. The calculations revealed that about one-third of the thermal feedback was by conduction in the ceramic block and two-thirds by wall-to-wall radiation, and indeed that (contrary to the approximate model of Winer that encouraged this line of research) the contribution of thermal conduction through the ceramic block was essential to the existence of a stable flame.

Chen also carried out calculations for a variety of parametric conditions beyond the range of his experiments. His prediction of the limiting flamespeeds for a 25.4-mm channel agreed closely with the measured values of Bath, validating them retroactively. Numerical calculations with Chen's model were not attempted for a 4.76-mm channel since the postulates of plug flow and perfect radial mixing were
obviously not applicable for the laminar regime.

Chen’s experimental work revealed a new process of both intrinsic and practical value, and his modeling and numerical solutions were a valuable complement. Most of the characteristic elements of behavior of thermally stabilized combustion were totally unexpected when we began. Luck, my perhaps excessive confidence in the asymptotic solution of Winer, and the persistence and ingenuity of Chen (both experimentally and theoretically) were all essential to the great success of this research.

THE SEARCH FOR MULTIPLE STATIONARY STATES

Melvin H. Bernstein undertook the task of searching for the predicted multiple stationary states as his doctoral research with a newly-acquired set of Wulff furnace elements. First, he reproduced Chen’s data within its band of variability. Then he searched for and found the expected second stationary state, then the five more which we had not expected despite their prediction by the numerical solution. One curious and (to this day) unexplained aspect of these measurements was the observation of four closely grouped upstream states and three even more closely grouped downstream states, whereas Chen’s model predicted four downstream and three upstream.

The Mobil R&D Company responded favorably and graciously to my request to analyze several samples of the burned gas from Bernstein’s experiments since we did not then have equipment for such measurements. We were excited to learn from these analyses that the thermally stabilized burner (TSB) produced no residual hydrocarbons since (as contrasted with all conventional burners) none of the fuel bypasses the zone of high temperature. Also, the TSB was found to produce essentially no “prompt” NO in the flamefront owing to its negligible thickness, and to produce exceptionally low concentrations of “thermal” NO (5-30 ppm) thereafter owing to the short post-flame times of residence. The concentration of total NO was found to be directly proportional to the post-flame residence time, as would be expected for a zero-order reaction. On the other hand, these low values of NO constituted a tradeoff with CO in that the same post-flame residence times were insufficient for complete oxidation to CO₂.

I encouraged Bernstein to improve upon Chen’s computer program, but he was unable to make even the original one operational. Finally, in desperation and impatience I telephoned Chen and solicited his help. He offered to retest his program as a first step and to call back the next day. After a suspicious delay of several days he called and shamefacedly reported that he had inadvertently printed a preliminary inoperable computer program in his dissertation, but that he was sending us the original, correct one, which he had retested and found operational.

However, Bernstein, in his struggles with the inoperable program, had discovered two significant errors. They were found to exist in the “original” program as well. Both of the errors inflated the heat-transfer coefficient for convection downstream from the flamefront as estimated from a standard correlation. When these errors were eliminated, no stable solutions could be computed. After much agony, we concluded that an inexplicably high coefficient was necessary to produce stable solutions, at least with Chen’s model. (It took another decade of work to explain this anomaly.)

We were now in the unbelievable situation of having found seven stationary states experimentally only because we were inspired to search for them by a theoretical model which now appeared to be invalid! But for the errors in his computer program, Chen might never have attained a solution, and Bernstein would never have searched for or found all of the six additional stationary states. (The subsequent history of our research suggests that we would have eventually searched for and found at least one additional state.) In retrospect, the irreproducibility of Chen’s data arose from the establishment on successive days of different members of the closely-grouped set of upstream states. The particular state depended upon minor variations in the process of startup that we had no reason at the time to consider relevant.

Again, luck was obviously an important element in our success, but two lessons stand out. First, the interaction of experimental and theoretical work is often synergetic and may produce more than either one alone. Second, independent efforts by two or more investigators may identify and explain anomalies that escape attention and/or resolution by only one. These two lessons have been reinforced by our subsequent experiences as described below.

THERMALLY STABILIZED COMBUSTION OF A LIQUID FUEL

As his doctoral research, Byung Choi extended the investigation of thermally stabilized combustion to liquid fuels by burning droplets of hexane generated by vibration of a capillary tube. Stroboscopic visualization of droplets of water in a preliminary experiment was utilized to confirm a theoretical
model, which was then used to guide the unobserved production of a chain of uniformly-sized and uniformly-spaced droplets of hexane within the burner. His results agreed remarkably well with those of Chen, suggesting that the thermally stabilized burner was essentially fuel-independent insofar as the droplets were small enough and volatile enough to evaporate completely ahead of the flamefront.

However, Choi was not able to establish more than one stationary state for a given set of conditions. He extended Chen’s model to encompass evaporation of the droplets and devised a greatly improved but still approximate method of solving the integro-differential equation (which proved to have general utility even outside of combustion and for solving purely integral equations as well). With this method, the effective energy of activation required to match the computed location of the flamefront with the experimental one was not dependent on grid size. He avoided the “stiffness” associated with the steep gradients of temperature and composition in the flamefront by using steps in composition rather than distance in the numerical integration. Even so, extreme sensitivity was encountered in the computational procedure; the stable solution was found to be dependent on the eighth significant figure of the temperature of the wall at the inlet, which quantity was used as the variable of iteration.

The numerical solution provided a complete, essentially fuel-independent locus of flamefronts versus the rate of flow of fuel and air in close agreement with the data for both gaseous propane and droplets of hexane. However, this relationship predicts only two stable locations for a given fuel-to-air ratio and rate of flow, one near the inlet and one near the outlet of the channel. The other five stable states predicted by Chen and observed by Bernstein are only slightly displaced from this locus, and we now postulate that the slight approximation which expedited the process of solution eliminates the fine structure which would have resulted in their prediction.

As contrasted with blowoff and flashback for conventional burners, the above-mentioned locus of stability predicts another unique characteristic for thermally stabilized combustion: for increasing rates of flow, both of the computed stable locations of the flamefront are predicted to shift inward toward a common point near the longitudinal midpoint of the channel followed by extinction; for decreasing rates of flow, both of the computed stable locations are predicted to shift outward to the respective ends of the channel, with extinction occurring some short of the ends. The predicted limiting behavior was not tested by Choi, even for the single downstream stable flame he established, because of the difficulty of adjusting the fuel and air proportionately while maintaining the same size and spacing for the droplets.

Choi also computed the chemical process of combustion using a global model for conversion of the hexane to CO and H$_2$O, and pseudo-steady-state free-radical models for the formation of NO$_x$ and the oxidation of CO. The predicted concentrations of NO$_x$ were greatly in excess of, and those of residual CO were grossly below, the measured values, suggesting that these models were inadequate, at least for the high temperatures and minimal backmixing encountered in thermally stabilized combustion.

The previously noted lessons concerning the conduct of research were reinforced in a slightly different context by the work of Choi. Again, a fresh approach by a second investigator, this time in solving the general model with some extensions, was very productive. The resulting solution included a complete locus for the stable flamefronts, and thereby the prediction of unique and unexpected limiting behavior. It also provided theoretical confirmation for the observed fuel-independence of the thermally stabilized burner. In addition, theoretical modeling of the atomization was a critical element in the design of the experiments.

THE SEARCH FOR MULTIPLE STATIONARY STATES WITH DROPLETS OF HEXANE

John W. Goepp, as his M.S.E. thesis, and with the help of Shu-Kin (Harry) Tang, completely reconstructed the experimental apparatus of Choi in order to provide more precise and flexible control of the rates of flow of air and hexane, and thereby facilitate the search for multiple stationary states in that system. Wulff furnace elements were no longer available, but a geometrically equivalent burner was cast from a commercial ceramic cement. Equipment for online analysis for NO, CO$_x$, CO, CO$_2$, and O$_2$ was added. The improved control permitted identification of as many as three upstream and two downstream multiple stationary states with hexane. Presumably, two more might have been found with better control and care. The locations of all of these stable flamefronts were in good accord with the predictions of Choi. The online chemical analyses were in agreement with those by Mobil, eliminating the nagging possibility that the latter were affected by the storage and transportation of
samples in Teflon bags.

**CHEMICAL MODELING OF THE POST-FLAME ZONE**

Tang utilized the improved apparatus constructed by Goepp and himself to investigate as his doctoral research the effects of an addition of small concentrations of fuel-nitrogen and fuel-sulfur to hexane on the formation of NO\textsubscript{X}. He covered a more complete range of residence times than his predecessors by making periodic, pseudo-steady-state measurements while the flamefront drifted upstream from a stable location near the outlet or downstream from one near the inlet as a result of a perturbation in the rate of flow. He also investigated a wider range of equivalence ratios (fuel-to-air ratios divided by the stoichiometric fuel-to-air ratio). He found that the conversion of fuel-nitrogen to NO\textsubscript{X} occurred primarily in the flamefront, was almost quantitative for equivalence ratios from 0.6 to 1.0, and fell off outside that range.\[10\] Fuel-sulfur was found to reduce the formation of thermal NO\textsubscript{X} slightly and fuel-NO\textsubscript{X} significantly,\[11\] a result which was in contrast with prior observations for other types of burners.

Tang initially resisted my proposal to model the post-flame reactions with a complete set of free-radical mechanisms, but relented when I mentioned that the alternative was explanation and possibly reinterpretation of his experimental results by another student. By trial-and-error he found that a kinetic model incorporating twenty-one reversible reactions was sufficient for the post-flame region for the combustion of pure hexane, and that twenty-three additional reactions were necessary for fuel-nitrogen and sixteen more for fuel-sulfur. He postulated a global model for the combustion of hexane to CO and H\textsubscript{2}O. When the mole fraction of hexane fell to 1 ppm due to combustion, the fuel-nitrogen and fuel-sulfur were postulated to be converted quantitatively and instantaneously to HCN and H\textsubscript{2}S respectively. The post-flame model was then initiated.

The predictions of NO\textsubscript{X} by Tang were in good agreement with his measurements for equivalence ratios up to 1.1, but in disagreement beyond.\[12\] The details of the computations revealed significant deviations of the concentrations of all of the free radicals from their pseudo-steady-state values throughout the post-flame zone, thus explaining the failure of prior predictions. The model predicted negligible formation of NO\textsubscript{X} (less than 10 ppb) in contrast to a significant fraction of the NO\textsubscript{X} in the measurements. Subsequent calculations suggested that all of the measured NO\textsubscript{X} was formed in the sampling tube, and this presumption has since been verified by spectrographic measurements within a burner. The deviation of the predicted concentrations of NO\textsubscript{X} for very fuel-rich mixtures from the measured values was presumed to be due to the failure of the post-flame zone of quantitative conversion of the fuel to CO and H\textsubscript{2}O. This speculation was eventually confirmed as described below. The predictions of NO\textsubscript{X} for hexane with added fuel-nitrogen were in good agreement with the measurements (except for very fuel-rich mixtures for the same reason as above).\[13\] The predictions for added fuel-sulfur were in qualitative agreement with the measurements, but the reductions in NO\textsubscript{X} were less.\[11\]

The work of Tang reemphasized the generalities noted above with respect to exploratory research. The synergetic value of combined experimentation and modeling was overwhelmingly apparent—particularly to Tang, who had initially resisted the incremental effort required by the latter. Again, common wisdom, this time in terms of the pseudo-steady-state postulate for the concentration of free radicals, was found to be misleading. The detailed kinetic model not only improved the predictions of NO\textsubscript{X}, CO, but also explained the failure of the early models. The prediction of NO\textsubscript{X} brought the process of measurement into question, and subsequent modeling of the process of sampling demonstrated that the measurements of NO\textsubscript{X} and CO were indeed in error due to an inadequate rate of quenching.

On the other hand, the extended range of experiments with respect to equivalence ratio identified the limit of validity of post-flame modeling alone, and suggested a new direction for this research. The qualitative agreement between the experimental and the theoretical effects of fuel-sulfur on the formation of NO\textsubscript{X} was essential in obtaining acceptance from the reviewers of an article for publication, since this result is contradictory to both experimental measurements and theoretical predictions for other types of combustion. On the other hand, the quantitative discrepancy between the measured and predicted effects of fuel-sulfur suggested an error in the modeling which was examined and resolved in subsequent work. The results for fuel-sulfur suggest another generality with respect to exploratory research. One must be prepared to justify (in great detail and beyond any question) radical results which invalidate prior theories or generalities, particularly those of the reviewers themselves.

**CHEMICAL MODELING OF THE PREFLAME ZONE**

Lisa D. Pfefferle proposed modeling chemical
kinetics in the preflame region as her doctoral research. Since prior work had indicated the behavior of the thermally stabilized burner to be essentially fuel-independent, methane (for which the rate mechanisms were presumed to be the simplest and most reliable) was chosen as a fuel. This research appeared in advance to be straightforward, but (as indicated below) unexpected results and difficulties arose at every turn. First, a clean and non-oscillatory flame could not be stabilized in the new, longer (508-mm) burner which had been cast. Several weeks were spent recalibrating the metering devices, analyzing the fuel, making a new 254-mm-long burner, etc.—all to no avail. In despair, she turned back to propane, which proved to burn stably as before. She then tried ethane, which also burned satisfactorily, and chose it in preference to propane and methane for the subsequent studies.

Analysis of the data for methane revealed that the steady rate of flow fell in the laminar regime upstream from the flamefront as contrasted with the turbulent regime for ethane, propane, and hexane. She speculated (and later confirmed by modeling) that this difference in behavior for methane was due to the absence of a C-C bond. One productive consequence of this adventure (which was very disturbing at the time) was the construction of a graphical correlation for the regimes of stability in the TSB for various fuels, equivalence ratios, channel-diameters, and channel-lengths.\textsuperscript{[14]} Another was a computational study of the adiabatic and non-adiabatic ignition of various fuels and mixtures thereof.\textsuperscript{[15,16]}

The studies of stability confirmed that turbulent flow is barely achieved in a 9.52-mm channel, even with C\textsubscript{2} \textsubscript{H} \textsubscript{4} fuels. It may be inferred that turbulent flow is unlikely to occur in ordinary chemical reactors since the much lower rates of reaction compared to those for combustion cannot be compensated for entirely by a larger diameter.\textsuperscript{[17]} Therefore, the postulate of plug flow cannot be justified on the basis of turbulent flow in either homogeneous or heterogeneous reactors despite that implication in most textbooks on chemical reaction engineering.

The computational studies of ignition by Pfefferle revealed that small concentrations of H\textsubscript{2} or C\textsubscript{2} \textsubscript{H} \textsubscript{4} in the mixture greatly enhance the ignitability. Had ordinary natural gas been used (rather than chemically pure methane) in her initial experimental studies in the thermally stabilized burner, the difficulties which caused such agony and led to the switch to ethane would not have been encountered. On the other hand, the long-range effects of this experience were many and all positive, including another example of the fundamental difference between thermally stabilized combustion and other processes, for which backmixing is a sufficient source of free radicals for rupture of the C-H bond.

Having established a model for the preflame region, Pfefferle encountered great difficulty with the stability of the solution of the set of differential equations representing the kinetic behavior ahead of the flamefront as contrasted with the single one for global kinetics. This characteristic difficulty in solving ordinary differential equations numerically is known as "stiffness" and arises from widely separated eigenvalues, or in physical terms in this instance from the critical dependence of the kinetics on minute concentrations of free radicals near the inlet of the burner. Brute-force calculations require intolerably small steps in space in that region. Pfefferle surmounted this difficulty by using an approximate analytical solution for the very inlet, followed by a standard scheme of marching.

Her computations revealed incredibly complex behavior near the flamefront and resulted in very good predictions of NO and CO even for very fuel-rich mixtures. The path of oxidation of ethane to CO and H\textsubscript{2}O was found to proceed through many intermediates such as CH\textsubscript{3}OH.\textsuperscript{[18]} This work confirms that, while a global kinetic model with adjustable empirical constants is able to predict the thermal behavior with reasonable accuracy, it cannot possibly be used to predict the concentrations of CO, NO, etc., either locally or overall. Pfefferle also modeled the preflame as well as the post-flame zone for the combustion of ethane with additions of ammonia\textsuperscript{[19]} and of ammonia and hydrogen sulfide.\textsuperscript{[20]} The predictions of NO\textsubscript{x} for pure ethane and for ethane plus ammonia were in good agreement with her own measured values, but the initial calculations for the added effect of hydrogen sulfide were not. She concluded that some important mechanisms were missing from the best current compilations. She also concluded that the greater reduction in fuel-NO\textsubscript{x} by fuel-sulfur in the TSB as compared to conventional burners was due to the higher temperatures in the immediate preflame zone and to the minimal backmixing. The contrasting chemical behavior for various conventional burners was successfully modeled with the same kinetic mechanisms by postulating an adjustable combination of a plug-flow reactor and a perfectly mixed one.

The productivity of Pfefferle’s research was greatly enhanced relative to original expectations by the completely unexpected behavior of methane \textit{vis-a-vis} other fuels in the TSB. This result was a
consequence of the fortuitous use of chemically pure methane rather than natural gas. Many important findings followed: 1) the absence of a C-C bond was identified as the source of fuel-sensitivity; 2) the absence of backmixing was identified as the source of the difficulty in burning methane in the TSB as contrasted with other burners; 3) the study of ignitability revealed the sensitivity of the TSB to small concentrations of $C_2+$ and $H_2$; and 4) the generalized analysis of stability resulted in the recognition that turbulent flow is unlikely in conventional reactors.

Other difficulties and anomalies were also a precursor to discovery. The stiffness of the free-radical, preflame kinetic model as compared to a global one resulted in the development of a new technique for that purpose. The failure of the predictions of the effect of fuel-sulfur on the formation of NOx to agree with experimental measurements in the TSB identified missing mechanisms as the culprit, and the different effects in a TSB and conventional burners were rationalized in terms of a combination of plug-flow and perfectly mixed reactors—a classical application of the methodology of chemical reaction engineering.

**TESTING THE POSTULATE OF PLUG FLOW**

The study of stability by Pfefferle[14] led to a further inference not mentioned above. Since the stable flow upstream from the flamefront is barely turbulent, at least for a 9.52-mm channel, the approximately seven-fold increase in absolute temperature and the associated approximately five-fold increase in dynamic viscosity result in a decrease of the Reynolds number behind the flamefront to much less than 2100 for all conditions. Laminarization was therefore to be expected. In all of the above-mentioned modeling, plug flow was postulated both upstream and downstream from the flamefront, except for the evaluation of the heat-transfer coefficient for convection, which was estimated from empirical correlations for fully developed turbulent flow upstream and for developing laminar flow downstream. The postulate of plug flow in the kinetic model was excused on the basis of the demonstration by Aris[21] that the error in the conversion of a reactant due to the postulate of plug flow rather than laminar (parabolic) flow is less than 11% for a first-order reaction and even less for higher orders.

Even so, I was very pleased when Lance R. Collins chose as his doctoral research to investigate laminarization behind the flamefront and its effect on the post-flame reactions. He computed the time-averaged field of velocity using a low-Reynolds-number k-ε model for turbulence[22] and then the corresponding chemical compositions using a free-radical kinetic model.[23] His measured pressure gradients and velocities at the centerline were in reasonable accord with the predictions, but both his measured and predicted concentrations of CO were as much as 25% higher than computed values based on plug flow. This unexpected result led to the realization that the generalization of Aris is not applicable to the residual concentration of a reactant. For example, the possible error in the residual concentrations of a reactant by a first-order reaction due to assuming plug flow rather than laminar flow is unbounded. The formation of NOx is not affected significantly since it is effectively zero-order and as such is independent of the velocity distribution.

The lesson here is that an authoritative generalization, although valid per se, may not be valid for conditions that differ subtly. We were ourselves misled for over a decade by the accuracy of the predictions of NO to the extent of presuming a chemical-kinetic rather than a fluid-mechanical explanation for the observed errors in the predictions of CO. It is noteworthy that none of the reviewers of our several papers seriously challenged the applicability of the postulate of plug flow in our modeling.

**GENERATION OF STEAM AND THE REDUCTION OF RESIDUAL CO**

The very low concentrations of NOx produced in the thermally stabilized combustor are, as noted above, somewhat at the expense of large residual concentrations of CO. Furthermore, NOx continues to form in the products of combustion after leaving the burner insofar as they remain at high temperature. This period may be significant with conventional boilers, etc. As his doctoral research, Mark R. Stenenger chose to investigate a process devised to quench the formation of NOx in the boiler, but to allow continued oxidation of CO while generating steam. The equipment consisted of seven metal tubes (contiguous with the channels of the combustor) that passed through a pool of boiling water contained in a cylindrical jacket.

The process worked exactly as planned chemically[24] but the heat transfer coefficient for forced convection from the products of combustion was much higher than expected.[25] A theoretical solution for the fluid mechanics and heat transfer using the same k-ε model as that of Collins provided an explanation.[26] The flow inside the combustor is in transition from turbulent to laminar flow. As the gas is cooled inside the metal tubes, the viscosity decreases,
the Reynolds number increases, and a transition back to turbulent flow occurs. Owing to this transition, a heat transfer coefficient higher than that for either fully developed laminar or fully developed turbulent flow is achieved.

The turbulent-laminar transition explains, at least in part, the excessive heat transfer coefficients required in the models of Chen⁴ and Choi.⁸ The heat transfer coefficient for forced convection inside small tubes is much greater than that for radiative transfer and unconfined convection in conventional boilers, even without enhancement by transition. The combined effect produces a reduction of several orders of magnitude in the size of the boiler.

Although the chemical behavior in Strenger’s research was much as expected, the thermal/fluid-mechanical behavior produced a favorable surprise which could be explained only through the theoretical modeling.

CONCLUSIONS

Combustion is a worthy subject of research by chemical engineers. It is of obvious practical importance, but has been the subject of only limited fundamental work. As a result of recent progress in chemical kinetics and machine computation, it is responsive to modeling with the classical techniques of chemical reaction engineering, and as a result of recent improvements in instrumental techniques, the in situ measurements necessary to test critically such modeling have become possible.

Thermally stabilized combustion proved, as indicated herein, to be a fortunate choice for this program of research because the fluid mechanics are simple relative to all conventional processes of combustion, while the thermal/chemical behavior differs radically in almost every respect. The characteristics of thermally stabilized combustion, which are noted herein only in a historical context, are summarized elsewhere.²²

Conclusions relative to the conduct of academic exploratory research were drawn above in connection with each of the separate undertakings, and only generalities in this regard will be listed here.

- Most discoveries arise from experimentally observed anomalies (the existence of multiple stationary states was an exception in that it arose from modeling).
- Theoretical modeling is usually necessary to understand and explain observed anomalies, and thereby to determine whether they represent physical behavior or experimental error.
- The combination of experimentation and modeling is generally more productive than their separate performance.
- Consecutive individual efforts on a general problem often provide new insights.

It follows that one of the most important roles of a faculty advisor is to encourage students to be on the alert for anomalies and to pursue and/or resolve them. A more difficult but worthwhile endeavor is to persuade theoretically inclined students to test their modeling experimentally, and experimentally inclined students to develop a model to explain and extend their measurements.

REFERENCES

16. Pfefferle, L.D., and S.W. Churchill, "The Ignition of Mixtures of Methane, Ethane, and Hydrogen in Air by Homo-
REVIEW: Thermodynamics

Continued from page 183.

Over the years we have used different editions of the text in our own teaching. A recent experience was with students whose first course was in the engineering core, so this book was used for a subsequent chemical engineering course in chemical thermodynamics. Our opinions on the success of the book are similar. In general, the examples and problems are very good—they are challenging but consistent with the text. The exposure to all combinations of phase equilibria is highly desirable. Also, the programs included in the second edition can be quite useful to students in addressing real (and therefore complex) systems, as well as fostering an exploratory mode of how nature actually behaves. This is especially valuable for students who must encounter the idealized or limited nonideal descriptions of physical chemistry thermodynamics.

The connections of the text to other courses is difficult to measure. Our experience is that differences of approach and notation usually overwhelm the similarities that may appear to students in later courses unless the same instructor is involved.

The text does achieve a significant level of detail, but this often leads to confusion about the fundamentals. The dilemma of how many formulae to put into the hands of students is solved by using extensive tables of equations for different cases. Often, the student’s reaction is to try to use these tables to look up a formula rather than to quickly derive the one they need for a problem. Another effect of this is to inadequately distinguish between fundamental concepts, approximate relationships, and specific illustrations. The result is that students become unsure of which are the big things that should be focused on and remembered. It also leads to a great deal of the material being strictly mathematical, with little physical connections that are either macroscopic or molecular.

Teachers will undoubtedly have differences with the author about his selection of correlations—that is inevitable in this area. In any case, the correlations are often presented without indication of whether they are to be used in real work or whether they are merely illustrative. The corresponding states treatment involves graphs from Hougan, Watson, and Ragatz containing $Z_r$, but equations containing the acentric factor. While the treatment for mixtures is complete, it is quite mathematical and follows a considerable discussion of the fugacity of pure components, so the whole exposition appears less focused than it might be.

All of the above issues may be dealt with by an experienced instructor who is comfortable with this difficult subject. In particular, highlighting the important material and simplifying complexities will be necessary. This takes a high level of concentration and a willingness to sacrifice some of the rigor of the text—this might ask for more commitment from students than they want to give. They will also have to deal with the text and the teacher appearing to conflict with one another.

The qualities of the text are numerous. It has been adopted in a limited number of situations, according to the latest AIChE Education Survey, and it is worthy of serious consideration at least as a reference.
Jill and Perry are senior engineering students. They met at their freshman orientation seminar, started dating soon afterward, and have been together ever since. A friend once remarked that they had the only perfect relationship he had ever seen: there wasn’t a single thing they agreed about!

They had an appointment to meet in the student lounge at 3:00 this afternoon. It is now well past 4:00. Jill is sitting at a table alone, trying to work but frequently looking over at the door and scowling. Perry finally walks in, greets a few friends, walks over to Jill’s table, and sits down.

Perry: (brightly) "Hi—get it all figured out yet?"
Jill: (glaring) "Where were you?"

Perry: "Oh, a few of us in Tau Beta Pi got going on the plans for the Awards Banquet and I lost track of the time...I’m not that late, am I?"
Jill: "Not for you, maybe, but for normal people an hour and twenty minutes might qualify for that late. Am I wrong or did we agree Sunday that we’d study for the design test from 3 to 4 today?"

Perry: "Come on, lighten up. We still have a couple of hours till supper, and the exam’s not until Friday—you know Professor Furze postponed it yesterday."
Jill: "I know he did, but we still had an appointment...and I’ve got a 331 lab report due Thursday and I planned to work on it between 4 and 6 today and I told you I’d go to a movie with you tonight. If we study for the test now and go to the movie, when am I supposed to do the report?"

Perry: "You and your ridiculous schedules...couldn’t you have worked on the report while you were waiting for me?"
Jill: "Look, my ridiculous schedules are the only reason we’re seniors now—if it were up to you to plan our lives we’d still be working on our sophomore course assignments and the only time we’d ever study for a test is all night the night before...that is, if you managed to remember we were having a test."

Perry: "That’s not true...besides, which of us got the highest grades on the first two design exams?"
Jill: "That has nothing to do with anything! Anyway, it’s 4:30 and we haven’t started yet...let’s see...maybe if we study for about 45 minutes now, then I’ll work on the report and we can get a pizza delivered, and that way we can leave at 7 to get to the movie...yeah, I think that should..."

Perry: "Why don’t we just get started and see where we are at 7 and decide then what to do—we can always skip the movie or go and study some more when we get back if we need to."
Jill: "No, we need to set it up now or else we’ll..."
Jill is a **judger** and Perry is a **perceiver**. *Judgers** tend to be organized and decisive: they like to set and keep agendas and reach closure on issues. Perceivers tend to be spontaneous, flexible, and open-minded; they like to keep their options open as long as possible and postpone decision-making until they feel sure they have all the relevant information.

Judgers plan ahead for most things. As students they budget their time for homework and study so they don't have to do it all at the last minute, and they can usually be relied on to turn in assignments on time. However, they tend to jump to conclusions, make decisions prematurely, and doggedly adhere to agendas that may no longer be appropriate. In their classes, judging students want clearly defined expectations, assignments, and grading criteria, and they don't like rambling lectures or class discussions that seem to have little point.

Perceivers do as little planning as possible, preferring to remain flexible in case something better comes up. They tend to work in fits and starts, alternating between periods of unfocused activity and frantic races to meet deadlines. They have trouble sticking to agendas, tend to start many more projects at one time than they can possibly finish, and are often in danger of missing assignments and doing poorly on tests due to insufficient study time. However, they are more likely than judgers to be aware of facts or data that don't fit their mental picture of a situation and in fact may go out of their way to look for such contradictions. When they don't fully understand something they tend to keep it open, gathering more information or simply waiting for inspiration to strike rather than accepting the first plausible explanation that occurs. Their flexibility and tolerance of ambiguity will make some of them superb researchers.

While students of both types may become excellent engineers and managers, the working habits of strong perceivers may make getting through school a major challenge for them, and anything that can be done to help them survive is worth attempting. They benefit from opportunities to follow their curiosity and work best on tasks that they have chosen themselves. They are not helped much by advice to work at a steady pace and not leave things for the last moment, which may be too radical a departure from their natural style to be manageable; however, it might help to ask them to figure out how late they can start to work on the assignment or study for the test and still do everything else they have to do. Perceivers rarely look at the holes they are digging themselves into through lack of planning. If they can be persuaded to itemize the things they intend to do, they might be convinced that without some planning they don't have a prayer of doing the things they have to do.

**Epilogue: Ten years later**

Jill and Perry got married shortly after graduation, managing (barely) to survive Perry's twenty-minute late arrival at the church and Jill's insistence on laying out an hour-by-hour schedule for their honeymoon. Jill got a job in a design and construction firm, eventually became a highly successful project manager, and is now in line for a vice-presidency. Perry went on to graduate school, got a PhD, and is now an eminent researcher at a national laboratory. It took years, but they finally figured out a good way to get along with each other.*

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* The degree to which one favors one or the other of these types can be determined with the **Myers-Briggs Type Indicator**, a personality inventory based on Jung’s theory of psychological types that has been administered to over one million people including many engineering students and professors.[1][2] Jill and Perry are illustrative of the two types, but not all judgers are just like Jill and not all perceivers are just like Perry. The two categories represent preferences, not mutually exclusive categories: the preferences may be strong or weak, and all people exhibit characteristics of both types to different degrees.

**REFERENCES**

1. Lawrence, People Types and Tiger Stripes, 2nd Ed., Center for Applications of Psychological Type, Gainesville, FL (1982)

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* Unfortunately, I haven’t been able to figure out what it might be.
RISK REDUCTION IN THE CHEMICAL ENGINEERING CURRICULUM

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Since Bhopal, words such as hazard, risk, waste, and chemical seem to be synonymous to the public and the media. There is increasing public, government, and industry awareness and concern over a number of problems: hazardous and toxic chemicals in the workplace, the environment, and home; increasing quantities of waste and costs of disposal, along with limited treatment capacity; industrial and transportation spills and accidents involving chemicals; contamination of water supplies; etc.

These concerns are being manifested by more (and tighter) local, state, and federal regulations. At the same time there is public opposition to things such as siting of incinerators, landfills, and industrial operations involving hazardous materials.

In response to the problem, the US Environmental Protection Agency created the phrase Risk Reduction Engineering as part of a multimedia-based "Pollution Prevention" program. The goal is to minimize wastes that present current and future risks to human health and the environment.

With regard to chemical engineering, the risk reduction concept encompasses a broader spectrum which includes safety, health, and loss prevention, as well as waste management and environmental controls. Risk reduction also deals with the technological/societal interface in the sense that management, regulations, and public relations are all components.

All of these concepts are implicit in chemical engineering education. However, despite the apparent job opportunities for chemical engineers in, for example, environmental engineering, risk reduction still seems to be largely ignored in the curriculum.

In particular, chemical engineering will play a major role in risk reduction by developing, assessing, and applying the technology that will predict, measure, control, and reduce risks from hazardous materials. It is thus timely (and perhaps mandatory) that, in the chemical engineering curriculum, greater emphasis be placed on topics such as waste reduction, safety, and health. While it is not necessary to make experts of all the students, the undergraduate program is a logical place to begin providing a background for recognition of potential hazards and an awareness of safe and clean process and product designs. Risk reduction can be addressed in most chemical engineering courses, from general chemistry to plant design, and the concepts should be easily understood by the students.[1]

I do not believe that new engineering programs in safety and health or waste-reduction engineering are needed, such as those that exist, for example, in environmental engineering. Much of the relevant knowledge and tools are implicit in the existing chemical engineering curricula. However, concepts such as hazardous materials, engineering controls, and materials substitution, are not usually covered, and could, at the least, be presented through example and homework problems such as those available from the AIChE Center for Chemical Process Safety.[2]

Risk reduction can be viewed as a unifying general concept that will provide an awareness, sensitivity, knowledge, and positive attitude for the students' future stewardship of health, safety, and the

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environment. Inclusion of these areas in the curriculum could be facilitated without adding numerous courses by incorporating them in the "Risk Reduction" spectrum. For example, in the materials and energy balances course, the properties, effects, and management of hazardous materials can be presented from the viewpoint of simultaneous concerns in the workplace, home, and environment.

In this paper, inclusion of risk reduction in the curriculum will be explored, and current related teaching efforts at the University of Louisville will be described. General principles and commonalities, synergies, and trade-offs between the components will be emphasized.

**RISK REDUCTION COURSES AT LOUISVILLE**

Several ideas for including safety and health in the chemical engineering curriculum have been previously presented. These ideas can also be put into the general framework of risk reduction since many of them also pertain to environmental concerns. At the University of Louisville, risk reduction was incorporated into the material and energy balances course when I last taught it. A one-hour course entitled "Safety, Health, and Environment," will be mandatory for juniors in the spring 1991 term, and a two-course sequence, "Safety and Health" and "Industrial Waste Management," was developed as first-year graduate (500-level) electives. (These two courses would also be suitable as senior electives, but our seniors do not have electives.) Graduate students can also take elective courses in "Membrane Separations" and "Chemodynamics," which are both related to risk reduction. Graduate students at the University of Louisville include our fifth-year Master of Engineering (M.Eng.) students.

A common feature in the material and energy balances, safety and health, and industrial waste management courses is a segment we call "In the News." During the first five minutes of class, articles from the local newspaper, Time magazine, Chemical & Engineering News, etc., which are related to either chemical safety and health or environmental issues are discussed. Since Louisville is a highly-industrialized city there is always some local or state news that the students can relate to, and this heightens their interest in the courses. In my opinion, the day-to-day real-world relevance of these courses is an important feature. In contrast to more traditional courses, students asked many questions. It is perhaps not so surprising to find that students are interested in risk reduction and that many have chosen chemical engineering as a career for that very reason.

Sophomore students interview for their first co-operative internship position while taking the material and energy balances course, and the M.Eng. students are interviewing for permanent positions at the same time. Both groups asked the interviewers about the company's health, safety, and environmental practices and opportunities. Feedback from the interviewers indicated that this helped to create a positive impression of our students. After their first co-op position, many of the sophomore students reported that they had dealt with risk reduction material covered in the material and energy balances course, e.g., materials safety data sheets, oxygen demand of waste-waters.

Specifically, some of the teaching modules from the AIChE Center for Chemical Process Safety were used in the material and energy balances course. The students were also required to fill out a materials safety data sheet. Next time I teach the course, problems developed from waste minimization assessments will be incorporated into the course, e.g., recovery of nickel salts from electroplating rinse-waters.

**COMMON FORMAT OF COURSES**

"Safety and Health" and "Industrial Waste Management" are broad-based survey courses offered at the first-year graduate level in the fall and spring semesters, respectively. We attempt to describe these courses in a manner that emphasizes generic and common features. Some of the risk reduction concepts can be covered in either course or in both.

The course outlines by topic are shown in Table 1, and the textbooks used are listed in Table 2. The same generic topics are covered in both courses, including regulations and standards, properties, effects and characteristics of hazardous and toxic materials, modeling, hierarchy of management and control options, preventive measures such as substitution and inventory control, control technology, and risk assessment. By necessity, there is some overlap of specifics between the two courses, even though...
repetition is minimized. For example, SARA Title III is discussed in both courses. However, OSHA regulations are discussed primarily in Safety and Health, and RCRA primarily in Industrial Waste Management. Threshold limit values, while referred to in Industrial Waste Management, is covered in depth in the safety and health course, while hazardous waste lists are discussed in Industrial Waste Management. Hazardous waste characteristics are discussed in both courses, but with different emphasis. However, in each course the commonalities and relationships between the different aspects of risk reduction are pointed out.

Both courses include student team audits and inspections. In Safety and Health, safety and health inspections of the chemical engineering laboratories were done, while in Industrial Waste Management the students did a waste minimization assessment at a local plant. The students found the inspections to be eye-opening, interesting, educational, and fun. Either of these courses is suitable for seniors, and to help meet accreditation guidelines they can easily be structured to include design and to enhance student communication skills. As an aside, student participation in safety, health, and waste reduction assessments is an excellent teaching tool. Several students

<table>
<thead>
<tr>
<th>TABLE 1</th>
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<tbody>
<tr>
<td><strong>Course Outline by Topics</strong></td>
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<tr>
<td><strong>Safety and Health Course</strong></td>
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<tr>
<td><strong>Generic and Common Topics</strong></td>
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<tr>
<td><strong>Materials Properties: Effects and Hazards</strong></td>
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<tr>
<td>• Toxicology</td>
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<td>• Epidemiology</td>
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<tr>
<td>• Fires and explosions</td>
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<tr>
<td>• Reactivity</td>
</tr>
<tr>
<td>• OSHA, TSCA, HMTA, SARA (Worker right to know)</td>
</tr>
<tr>
<td><strong>Regulations and Liability</strong></td>
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<tr>
<td>• Dose response</td>
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<tr>
<td>• Risk</td>
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<tr>
<td>• Health/environment effects of pollutants</td>
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<tr>
<td>• State of the environment</td>
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<tr>
<td>• Hazardous waste characteristics</td>
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<tr>
<td><strong>Emission Sources, Types, and Characteristics: Criteria and Definitions</strong></td>
</tr>
<tr>
<td>• Gases, vapors, particulates</td>
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<tr>
<td>• Threshold limit values</td>
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<tr>
<td>• Other hazard classifications, e.g., NFPA</td>
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<tr>
<td>• Materials safety data sheets</td>
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<tr>
<td>• DOT guidelines</td>
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<tr>
<td>• Hazardous/toxic waste lists and characteristics</td>
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<tr>
<td>• Hazardous waste generator reports</td>
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<tr>
<td>• Air toxics</td>
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<tr>
<td>• Wastewater parameters</td>
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<tr>
<td><strong>Modeling</strong></td>
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<tr>
<td>• Source models for worker exposure</td>
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<tr>
<td>• Radioactivity concentration guide for water</td>
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<tr>
<td>• Ambient carbon monoxide standard</td>
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<td>• Coburn, Forster, Kane equation</td>
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<td>• Dispersion</td>
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<td>• Air pollution: Smog 0, NOx, VOCs</td>
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<tr>
<td><strong>Management, Hazards Identification, Inspections</strong></td>
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<tr>
<td>• Checklists, surveys, reviews, HAZOP</td>
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<tr>
<td>• Accident investigations</td>
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<tr>
<td>• Risk assessment fault and event trees, probability</td>
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<tr>
<td>• Hierarchy for prevention and control</td>
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<tr>
<td>• Environmental audits</td>
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<tr>
<td>• Waste minimization assessments</td>
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<tr>
<td><strong>Prevention, Protection, Engineering Controls</strong></td>
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<tr>
<td>• Protective equipment and clothing, monitoring</td>
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<tr>
<td>• Isolation, ventilation</td>
</tr>
<tr>
<td>• Relief valves</td>
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<tr>
<td>• Suppression of fires and explosions</td>
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<tr>
<td>• Materials substitution, product/process modification</td>
</tr>
<tr>
<td>• Inventory control</td>
</tr>
<tr>
<td>• Emergency response, spill prevention control</td>
</tr>
<tr>
<td>• Underground storage tanks</td>
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<tr>
<td>• Transportation of wastes</td>
</tr>
<tr>
<td>• Industrial wastewater pretreatment</td>
</tr>
<tr>
<td>• Waste reduction, resource recovery, recycling</td>
</tr>
<tr>
<td>• Thermal treatment</td>
</tr>
<tr>
<td>• Landfill disposal</td>
</tr>
<tr>
<td>• Chemical, physical, and biological treatment</td>
</tr>
<tr>
<td>• Injection well disposal</td>
</tr>
<tr>
<td><strong>Site Remediation</strong></td>
</tr>
<tr>
<td>• Hazard ranking system</td>
</tr>
<tr>
<td>• Containment/treatment technologies</td>
</tr>
<tr>
<td>• Financial considerations</td>
</tr>
<tr>
<td><strong>Student Team Project</strong></td>
</tr>
<tr>
<td>• Safety and health inspection of chemical engineering building</td>
</tr>
<tr>
<td>• Waste minimization assessment of local manufacturing facility</td>
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</table>
are participating in a funded waste minimization assessment program and are involved with the preparation of preliminary engineering feasibility studies for a variety of different manufacturing facilities. Two of these students have received job offers from major companies to work in waste reduction after graduation.

In general, the courses are more descriptive and qualitative than quantitative and theoretical, although a limited number of theoretical/calculational problems are assigned. Safety and Health is the more technical course, primarily because of the recent availability of a new chemical engineering textbook. However, the students are made aware of the relevant principles and techniques from traditional courses and how to apply them. For example, material from Transport Phenomena is used to estimate relative evaporation rates of solvents as a measure of fire and health hazards and to estimate solvent loss. With regard to risk reduction, the students already know much of the necessary technical content, but need to be shown where and how to use it. In this sense, the instructor serves as more of a facilitator than a subject-matter expert.

Since safety, health, waste management, etc., cover such a wide range of topics, it would be difficult for any one instructor to have sufficient overall expertise. Also, the available textbooks in these subjects do not cover many relevant topics. Therefore, guest speakers are used to lecture in areas that they work in, such as waste-water treatment, air-pollution control, and toxicology. The part-time students are an excellent classroom resource, and some of them also make presentations related to their work. They can often answer classroom questions better than I can, and they provide excellent input to classroom discussions. A partial listing of some of the topics presented by guest and student speakers in given in Table 3.

Field trips and plant visits are also part of both courses (see Table 4). During some field trips, in-plant lectures are given. The guest lectures and field trips were highly valued by the majority of the stu-

### TABLE 2

**Textbooks and Other Required Materials**

**Safety and Health**
- ACGIH, *Threshold Limit Values and Biological Exposure Indices* (latest edition)
- NIOSH Pocket Guide to Chemical Hazards

**Industrial Waste Management**

**Other**
- Hoover, Hancock, Hutton, Dickerson, and Harris, *Health, Safety and Environmental Control*, Van Nostrand-Reinhold, 1989

### TABLE 3

**Guest Lectures**

**Safety and Health**
- "Applications of Toxicology Data to Chemical Operations," by Health and Safety Director, Rohm & Haas
- "Material Safety Data Sheets," by Occupational Health Consultant
- "Du Pont Philosophy and Management System for Safety and Health," by Maintenance Supervisor, Du Pont
- "Fire Safety and Industrial Hygiene," by Senior Loss Control Engineer, Travelers Insurance
- "Cleanup of Superfund Hazardous Waste Sites," by Emergency Response Engineer, EPA Contractor
- "Health Hazard Identification," by Field Inspector, Kentucky Department of Labor

**Industrial Waste Management**
- "Environmental Management in the Chemical Industry," by Environmental Affairs Manager, Du Pont
- "Environmental Regulations," by Environmental Attorney or Assistant Commissioner, Kentucky Department for Environmental Protection
- "Legal Liability for Environmental Practitioners," by Environmental Attorney
- "Industrial Waste-Water Pretreatment and the Morris Forman Waste-Water Treatment Plant," by the Director, Industrial Wastes Metropolitan Sewer District
- "Air Pollution Modeling and the Local Smog Situation," by Director, Jefferson County Air Pollution Control Board
- "Prevention, Containment and Response to Hazardous Materials Spills," by Spill Control Engineer, Metropolitan Sewer District
- "Leaking Underground Storage Tanks," by Consultant
- "Waste Incineration," by USEPA Speaker or Technical Operations Manager, Louisville Incinerator
- "EPA Programs in Waste Minimization," by Risk Reduction Engineer, USEPA
- "Environmental Audits for Property Acquisition," by Consultant
- "Remediation and Closure at a RCRA Landfill," by Environmental Manager, Du Pont
- "State of the Environment in Kentucky," by Environmental Activist Attorney
- "Solid Waste Disposal and Landfill Design: Engineering and the Decision Making Process," by Director, Division of Waste Management, Kentucky Department for Environmental Protection
dents, and they particularly appreciated the networking aspect, as did I.

Many useful movies and video tapes are available in safety, health, and environmental areas, and they are also used in class (see Table 5). The videos, many of which are excellent dramatizations, often depict things much better than the instructor or a text can. Study guides for the videos, in the form of assigned questions, are given to the students. Because of the deficiencies within the textbooks and the lack of breadth and currency of the topics, numerous additional materials are also given to the students (see Table 6).

PART-TIME STUDENTS ATTRACTION TO COURSE

The primary prerequisite for Safety and Health and Industrial Waste Management is a BS in science, math, engineering, or its equivalent. Thus, the courses are taken by first-year graduate and M.Eng students from other departments, along with part-time students from industry, consulting firms, and government agencies. Many part-time students come from as far as sixty miles away.

The courses are offered on a one night per week basis, 2-hours 45-minutes per class, so as to attract part-time students. Announcements of the courses are placed in newsletters of various regional and statewide professional organizations such as the Kentucky Waste Reduction Centers and the Air and Waste Management Association.

The first offering of Industrial Waste Management drew about thirty-five students, two-thirds of which were part-time students. Several of the part-time students also took Safety and Health which was taught the following year with fifteen students (nine of them part-time). In the second offering, Industrial Waste Management had eighteen students (fourteen of them part-time) and Safety and Health had ten students (nine of them part-time). These courses are being recommended to co-workers, and the part-time students have requested additional courses in risk reduction. In response, we plan to offer a course entitled Waste Reduction, Treatment, and Disposal in the future.

Many of the part-time students are not pursuing a degree and thus can register through Continuing Studies rather than through the usual, more tedious, routes. Students not applying the credits towards a degree, along with non-chemical engineering students (who may lack some of the technical

### TABLE 4

<table>
<thead>
<tr>
<th>Field Trips and Plant Visits</th>
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<tbody>
<tr>
<td>Safety and Health</td>
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<tr>
<td>• Safety Features in Emulsion Polymerization Process: Rohm &amp; Haas</td>
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<tr>
<td>• Emergency Response Simulation: Jefferson County Hazardous Material Mutual Aid Group</td>
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<tr>
<td>• Hazardous Waste Incinerator Sitting Hearing</td>
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<tr>
<td>Industrial Waste Management</td>
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<tr>
<td>• Waste Water Treatment Plant: Metropolitan Sewer District</td>
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<tr>
<td>• Industrial Waste-Water Pretreatment Plant: General Electric</td>
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<tr>
<td>• Municipal Solid Waste Incinerator</td>
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<tr>
<td>• Industrial Landfill: Waste Management Company</td>
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<tr>
<td>• Waste Minimization Assessment: BASF</td>
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### TABLE 5

<table>
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<tr>
<th>Video Tapes and Films¹</th>
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<tbody>
<tr>
<td>Safety and Health</td>
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<tr>
<td>• Acceptable Risk, ABC Television</td>
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<tr>
<td>• Safety in the Chemical Process Industries, AIChE-7 Tape Series</td>
</tr>
<tr>
<td>• Safety and Loss Prevention, First Impressions, BASF</td>
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<tr>
<td>• Chemical Toxicity and How It Affects You and Your Job, Celanese</td>
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<tr>
<td>• MSDS: Cornerstone of Chemical Safety, ITS</td>
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<tr>
<td>• Health Hazard Evaluation: Environmental-Epidemiological Study of Workers Exposed to Toluene Disocyanate, West Virginia University</td>
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<tr>
<td>• Dual Protection, NIOSH, (Paints and Coatings)</td>
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<tr>
<td>• First Considerations, NIOSH (Pesticide Formulating Plants)</td>
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<tr>
<td>• Case Studies—Flixborough, Bhopal</td>
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<td>• BLEVE, NFPA</td>
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<td>• Confined Space Entry, NIOSH</td>
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<td>• Oxidizers: Identification, Properties, and Safe Handling, CMA</td>
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<tr>
<td>Industrial Waste Management</td>
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<tr>
<td>• Doing Something, CMA</td>
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<tr>
<td>• The Need to Know, CMA</td>
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<tr>
<td>• The Burial Ground, (Hazardous Waste Dumping)</td>
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<td>• The Toxics Release Inventory: Meeting the Challenge, EPA</td>
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<tr>
<td>• In Your Own Back Yard, NFPA (Underground Storage Tanks)</td>
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<td>• Tank Closure Without Tears: An Inspectors Guide</td>
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<tr>
<td>• Beyond Business as Usual, EPA (Hazardous Waste Management)</td>
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<tr>
<td>• Marine Shale Processor, Let's Clean Up America, (Incineration/Recycling)</td>
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<td>• Pollution Prevention by Waste Minimization, 3M Company</td>
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<tr>
<td>• Less is More: Pollution Prevention Pays, EPA (Waste Minimization)</td>
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<tr>
<td>Common to Both Courses</td>
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<tr>
<td>• Carcinogens, Anti-Carcinogens, and Risk Assessment, Council for Chemical Research</td>
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<tr>
<td>• First on the Scene, CMA (Emergency Response)</td>
</tr>
<tr>
<td>• Teamwork, CMA (Emergency Response)</td>
</tr>
<tr>
<td>• Dry Paint Stripping, Promaco/Schlick (Waste Reduction, Safety)</td>
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</table>

¹ Not all used in a given semester
background), can take the course on a pass/fail or audit basis to minimize the pressure of grades. The courses are taught on an informal, relaxed basis (similar to a workshop or seminar) which enhanced the students' enjoyment. For example, on some nights when movies or video tapes were being shown, popcorn was served. Because of the maturity of the students, it was a pleasure to be on a more collegial basis with them, and as pointed out earlier, the part-time students are an excellent classroom and networking resource.

SYNERGIES BETWEEN APPLICATIONS

Some examples of the unifying concepts of risk reduction, resultant synergies, and trade-offs are briefly explored. These approaches can be used in either of the two survey courses or as a component of any appropriate required course.

One example of synergy is in finishing operations such as paint and coating applications. The same properties that make wastes and emissions from these operations hazardous also contribute to exposure that endangers employee health and plant safety. Thus, waste reduction measures will simultaneously benefit employee safety and health, and vice versa. These measures include substitute materials and alternative methods, such as aqueous-based rather than solvent-based paints, powder coatings, and airless or electrostatic spray guns. Another synergy that occurs with waste reduction is conservation of raw materials. For example, increased recycling of plastics can simultaneously reduce dependence on foreign crude oil.

Trade-offs or conflicts can also be shown (for example) between waste minimization and quality management, and between safety and waste disposition considerations. Reworking of off-specification and waste solids from tank cleaning into useful products is a waste minimization technique. Spills on the one hand must be properly retained and disposed of so as not to damage the environment. On the other hand, a reactive (but improper) response to a hazardous materials spill might be to flush it immediately down the drain.

WHAT IT WILL TAKE

Some preliminary ideas concerning the inclusion of the risk reduction spectrum into the curriculum have been presented and exemplified in this paper. Because of the increasing importance of risk reduction to chemical engineers, further exploration of ways to incorporate these concepts seems mandatory. Availability of teaching materials such as the problem sets available from the AIChE Center for Chemical Process Safety can facilitate this process. Hopefully, such materials will be available from the newly-established AIChE Center for Waste Reduction Technology.

REFERENCES

The United States aerospace, automotive, biomaterials, chemical, electronics, energy, metals, and telecommunications industries collectively employ more than 7 million people in materials science and engineering and have sales in excess of $1.4 trillion. Recent reports have called the 1990s the "Age of Materials" and have concluded that the field of materials science and engineering is entering a period of unprecedented intellectual challenge and productivity. Chemical engineers, with their background in reaction engineering and transport processes, have the skills necessary to make significant contributions in this area.

A strong component of materials science and engineering is ceramics science and engineering. Although many applications of ceramics have in the past been low-tech, a vast number of new high-tech ceramics have been developed in recent years, opening up a large number of new and exciting applications for a wide variety of industries. Ceramic superconductors may provide new methods of energy transmission and new types of electronic devices. Electronic ceramics such as BaTiO₃ and SrTiO₃ are used to make capacitors and sensors. Ferroelectric ceramics can be used to produce memories for computers. A variety of metal oxides, nitrides and silicides are used in computer chips and to make substrates for the chips themselves.

Ceramics can also be used to make chemical sensors for detecting small amounts of hazardous substances for applications in hazardous waste control. They are also used as catalysts for chemical reactions or as catalyst supports in the chemical industry. These and other applications have led to a tremendous interest in the synthesis, processing, and characterization of ceramic materials in the form of powders and films.

The chemical engineering department at the University of New Mexico dramatically expanded its program in ceramics science and engineering following the establishment of a National Science Foundation-supported UNM/NSF Center for Micro-Engineered Ceramics (CMEC). Numerous research projects, many in the areas mentioned above, are now available to interested students. These opportunities are particularly interesting since demand is high for students with a background in ceramics, with fewer than forty PhDs being granted in the United States each year in Ceramics Science and Engineering (with roughly half of them going to foreign students).

This article briefly describes some of the research opportunities in ceramics science and engineering at the University of New Mexico. Students interested in participating in one of these projects should contact the faculty member responsible for that research area. The following sections describe some of the research projects available at the University of New Mexico.

Toivo T. Kodas received his BS (1981) and PhD (1986) from the University of California, Los Angeles. During that period he also worked at the ALCOA Research Center. He was a visiting scientist at the IBM Almaden Research Center from 1986 until 1988 when he joined the faculty at the University of New Mexico.

C. Jeffrey Brinker received his BS, MS, and PhD degrees from Rutgers University, and joined the Ceramic Development Division at Sandia National Laboratories in 1979. He is presently a member of the technical staff and a University of New Mexico/Sandia National Laboratory professor of chemistry and chemical engineering.

Abhaya K. Datye received his BS from the Indian Institute of Technology, Bombay (1975), his MS from the University of Cincinnati (1980), and his PhD from the University of Michigan (1984), and has been a member of the chemical engineering faculty at the University of New Mexico since 1984.

Douglas M. Smith received his BS (1975) and MS (1977) from Clarkson University and his PhD (1982) from the University of New Mexico. Previous positions include Unilever Research and Montana State University. He is currently professor of chemical engineering and serves as Director of the UNM/NSF Center for Micro-Engineered Ceramics.
A strong component of materials science and engineering is ceramics science and engineering. Although many applications of ceramics have in the past been low-tech, a vast number of new high-tech ceramics have been developed in recent years, opening up a large number of new and exciting applications for a wide variety of industries.

opportunities in ceramics science and engineering at the University of New Mexico and the unique interdisciplinary nature of the projects which involve investigators from chemical engineering and other departments, from centers at UNM involved in materials, and from Sandia and Los Alamos National Laboratories.

RESEARCH AREAS

The authors of this paper have extensive programs in ceramics science and engineering. Their projects span ceramics synthesis, processing, and characterization.

Jeffrey Brinker is investigating sol-gel processing of ceramics—films, fibers, powders, and bulk; physics and chemistry of film deposition from liquid precursors; defects in glasses; controlled porosity materials for sensors, membranes, and adsorbents; nanoscale materials; multifunctional composites; and fractals.

Sol-gel processing (see Figure 1) refers to the room temperature formation of inorganic materials from molecular precursors. Inorganic salts or metal organic compounds dissolved in aqueous or organic solvents are hydrolyzed and condensed to form polymers composed of M-O-M bonds. These polymers may be deposited on substrates to form thin films, drawn into fibers, or cast in molds and dried to form "near-net-shape solids." Prior to drying, the structures of the polymers are often described by fractal geometry, a consequence of kinetically-limited growth mechanisms such as reaction-limited cluster aggregation. The properties of fractal objects may be exploited to prepare novel inorganic materials. Only when these materials are processed in the vicinity of the glass transformation temperature do their structures approach those of their conventionally prepared counterparts.

Abhaya Datye is interested in: heterogeneous catalysis and surface science; structure and properties of thin films and interfaces in ceramics and semiconductors; and materials characterization by electron microscopy.

Phenomena occurring at the interfaces between dissimilar materials have enormous implications in materials we use every day. For instance, the strength of the bond between a metal and a ceramic determines the properties of glass metal seals as well as the high-temperature stability of heterogeneous catalysts. Sometimes a weaker interface is desired (as in

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a fiber-reinforced composite) to redistribute stresses at the interface and deflect cracks to make a brittle ceramic tougher. In semiconductors the performance of a device is often determined by the impurities and defects at an interface. Therefore, engineering of such complex materials requires a good understanding of the interface region and the means of tailoring the interface to achieve desired properties. Since even a monolayer of a hydrocarbon can affect the wetting of water on a solid substrate, it is apparent that interfacial properties are determined by changes occurring over the scale of atomic dimensions. It is therefore necessary to use probes having high spatial resolution as well as those that give chemical information from the near-surface region. In the research at the University of New Mexico, high-resolution transmission electron microscopy and surface-sensitive spectroscopies are used to study these materials and correlate their structure with properties relevant to their commercial applications.

One project involves the study of thin-film coatings of non-oxide ceramics and their interactions with ceramic substrates.[9] We are examining the potential of boron nitride for use as a high-temperature coating material for fiber-reinforced composites. The interaction of BN with oxide ceramics is quite strong, and BN appears to readily wet and coat these substrates. However, a detailed study[10] of the atomic structure of this interface reveals that the interatomic spacing between the BN sheets and MgO is larger than distances normally associated with chemical bonding (see Figure 2).

Other projects deal with fundamental studies of oxide surfaces in order to understand the surface chemistry involved in preparing monolayer and multilayer films of other oxides for potential catalytic applications.[11,12] Studies of surface structure in small metal particles are being conducted in the laboratory to examine the effect of pretreatments and the ceramic support on catalytic behavior.[13] Finally, the high spatial resolution of TEM is exploited to study the structure and properties of materials ranging from strained layer superlattices[14] to fine pores in oxides.[15]

Chemical vapor deposition is used extensively in...
industry for the formation of thin films of a wide variety of materials. This process begins with a volatile molecular species that is transported to a substrate where it decomposes and results in deposition of material with desorption of volatile byproducts. The chemistry occurring during deposition determines the deposition rate, minimum deposition temperature, adhesion to the substrate, and electronic properties. Yet the chemistry occurring during most CVD processes is poorly understood. Our research involves the use of high pressure and ultrahigh vacuum systems utilizing mass spectrometry, Auger electron spectroscopy, temperature-programmed desorption, FTIR, and Raman spectroscopy to study the surface and gas phase chemistry. The goal is to develop a better understanding of the role of chemistry in determining the properties of the deposited material. Current projects are the examination of deposition of PLZT with Radiant Technology, Cu with Motorola, and YBa$_2$Cu$_3$O$_{7-x}$ with Los Alamos National Laboratories.

Aerosols (fine particles suspended in a gas) play a fundamental role in fine metallic and ceramic particle production, optical fiber production, thin film formation, and contamination control in cleanrooms. We are currently examining the interaction between the chemistry and aerosol dynamics in systems for gas phase particle production, deposition of these particles onto surfaces to form coatings, and during laser-induced deposition processes.

**Douglas Smith** is currently examining characterization of porous materials, transport phenomena in porous media, sol-gel, and powder processing.

The pore structure of materials is of considerable interest for a large number of applications which include ceramics processing, catalysis, membrane separations, radioactive waste isolation, and coal gasification. The basic approach is to study the physics of both established and innovative pore structure analysis tools in an attempt to extract more detailed information about porous solid systems.

Conventional techniques for pore structure analysis include mercury porosimetry, nitrogen adsorption/condensation, and microscopy (optical, scanning, and transmission electron). Each of these techniques suffers from different disadvantages which limit accuracy and preclude their use for in-situ pore structure analysis. Therefore, considerable incentive exists for the development of new techniques for pore structure analysis. Professor Smith’s laboratory has pioneered the development of low-field, NMR spin-lattice relaxation measurements of fluid contained in pores as a structure analysis technique. This approach allows the study of pores of “wet” materials and allows imaging of pore structure as a function of time while the structure evolves.

In addition to pore structure analysis, the study of the physical nature of surfaces is of interest. In particular, the fractal nature of surfaces is being studied via molecular probe techniques. A parallel effort using SAXS (small angle x-ray scattering) and SANS (small angle neutron scattering) is underway in collaboration with investigators at Sandia National Laboratories. The growth of fine particles and polymers in solution is studied via both SAXS and light scattering.

Using expertise in pore structure analysis, a number of ceramics processing problems are being examined. These include pore structure evolution and elimination during sintering of ceramic green bodies, dispersion of powder agglomerates, packings of powders during green body formation, and pore structure development during sol-gel processing of xerogels and aerogels (both bulk and coatings). Ceramic powder synthesis is conducted using a range of techniques including reactive laser
ablation, sol-gel processing, precipitation, and aerosol processing.

CENTER FOR MICRO-ENGINEERED CERAMICS

Much of the research in ceramics science and engineering is being carried out in the National Science Foundation Center for Micro-Engineered Ceramics, which is housed in the chemical engineering department. The Center consists of fifteen professors from the University of New Mexico (seven from chemical engineering, four from chemistry, one each from mechanical engineering, physics, and geology), over ten staff members from Sandia National Laboratory, and over ten staff members from Los Alamos National Laboratory. A critical feature of the Center is the membership of more than fifteen industrial members. This allows the Center to combine the expertise of the national labs, the university, and industry to attack ceramics-related problems of interest to industry. The goals are to attack useful problems, to transfer technology between industry, the National Labs and the University, and to train students in ceramics science and engineering. A key feature of the Center is the hands-on policy for use of equipment. The Center is equipped with a variety of state-of-the-science equipment, shown in Table 1.

INTERACTIONS WITH OTHER DEPARTMENTS AND NATIONAL LABORATORIES

Another feature of the CMEC and the chemical engineering department is the extensive interactions with other departments at the university. The projects in the CMEC are interdisciplinary with faculty from chemical engineering, chemistry, physics, geology, mechanical engineering, and the national laboratories involved in each project. In addition, significant interactions occur with the Center for High Technology Materials in electrical engineering whose strength is optoelectronic materials.

The extensive interactions of the chemical engineering department and CMEC with the national laboratories has numerous advantages. The strengths of SNL include electronic ceramics and glasses, while LANL is primarily involved in structural and superconducting ceramics. These skills complement the strength of the University in chemical routes to ceramics and materials characterization. Scientists and engineers at the Center and in the chemical engineering department have access to state-of-the-science equipment at the national laboratories. In ad-

Another feature... is the extensive interactions with other departments... the projects are interdisciplinary, with faculty from chemical engineering, chemistry, physics, geology, mechanical engineering, and the national laboratories involved in each project.

<table>
<thead>
<tr>
<th>TABLE 1: CMEC Facilities</th>
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<tr>
<td>• High-field solution and solids FT-NMR spectrometers: GE NT-360, JEOL GX-400, Bruker AC-250P, Varian 400 MHz Unity 1</td>
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<tr>
<td>• Low-field pulse NMR spectrometers: 10 MHz, 20 MHz, 4-60 MHz, for sol-gel and green body structure analysis</td>
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<tr>
<td>• Hitachi S-800 field emission SEM (20 angstrom resolution) with low Z x-ray analysis and advanced image analysis</td>
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<tr>
<td>• Electron Beam Microanalysis Facility, including JEOL 2000FX TEM with TN5500 EDS, JEOL Superprobe with 5 spectrometers, Hitachi S-450 SEM</td>
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<td>• Electron spin resonance spectrometer</td>
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<td>• FT-Infrared spectrometers: NIC-6000, Perkin-Elmer, Galaxy 6020 coupled to high-vacuum IR cell for powder studies</td>
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<tr>
<td>• Single-crystal and powder x-ray diffractometers</td>
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<td>• Powders and Granular Materials Laboratory, includes: Autoscan-33 mercury porosimeter, Quantitome 720 image analyzer, Autosorb-1 automated nitrogen sorption analyzer, Sedigraph particle-size analyzer, Coulter Counter, 4 adsorption instruments, gas permeation apparatus, Micromeritics Accupyc 1330 - Pycnometer, Micromeritic ASAP-2000 adsorption analyzer</td>
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<td>• Small-angle x-ray scattering (SAXS)</td>
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<td>• Two RF high-temperature (3000°C) furnaces</td>
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<td>• High-temperature thermal analysis instrumentation (TGA, DTA, DSC, Dilatometer)</td>
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<td>• Laser birefringence facility for the in-situ study of stress in sol-gel and polymer processing</td>
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<tr>
<td>• Aerosol powder reactors including high-temperature (1700°C) and scale-up aerosol reactor for production of oxide ceramic powders (kilograms per day)</td>
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<td>• Coupled TPD/Auger apparatus for surface analysis</td>
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<tr>
<td>• Light scattering: Spectraphysics 2000 krypton laser, Brookhaven Gonimeter, BI-2030 AT controller</td>
</tr>
<tr>
<td>• Nuclear Magnetic Resonance Imaging (NMRI) for in-situ studies of transport phenomena in porous materials</td>
</tr>
<tr>
<td>• Four gas membrane test stands.</td>
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dition, fellowships such as the UNM/LANL PhD fellowship are available to outstanding students with a stipend of $16-18 k/yr.

Researchers at the chemical engineering department and CMEC have access to various facilities at the national laboratories. The facilities of LANL include the Exploratory Research and Development Center for Superconducting Ceramics, the LANSCE-Los Alamos Neutron Scattering Center, the Center for Materials Science, and the Ion Beam Materials Laboratory. The facilities of SNL include the Surface Modification and Analysis Facility, Ceramics and Glass Processing Facility, SNULANL dedicated EXAFS lines at Brookhaven and Stanford, and a 30,000 ft² materials research and development laboratory which is jointly administered by UNM and SNL.

REFERENCES
The course "An Introduction to Molecular Transport Phenomena" is intended for upper-level undergraduates or first-year graduate students in engineering and science. The overall goal of the course is to provide a comprehensive description of the molecular basis of transport phenomena for students who have no previous background in statistical mechanics or statistical physics.

It is clear that recent dramatic advances in computational abilities (e.g., supercomputers and connection machines\(^1\)) and in atomic-level experimentation (e.g., atomic force microscopy and scanning tunneling microscopy\(^2\)) require that undergraduate engineers obtain a better molecular understanding or interpretation of engineering processes. One example is a surge in supercomputer purchases in the chemical industry; an example of the benefits of supercomputer computations is a reported $1-2 million savings in development costs for a new catalytic process\(^3\). By studying the thermodynamic properties of the system through use of molecular simulations on a supercomputer, some critically unusual properties were discovered that would have been difficult to detect through physical experiments.

These new computational and experimental capabilities make it possible to examine, design, or enhance systems and processes beginning at a molecular level description—an approach that may be called "molecular engineering." In general, molecular engineering represents a new and powerful method of analysis where a rational and scientific framework can be utilized for the systematic study of highly complex engineering systems.

Molecular engineering also plays a critical role in the development of newly emerging areas of chemical engineering (such as advanced polymeric and ceramic materials, and biochemical and biomedical engineering) where a molecular and macromolecular description is a necessity rather than just an alternate method of analysis.\(^4\) There is a current need in the undergraduate curriculum for both qualitative and quantitative descriptions of processes and phenomena involving gases, liquids, and solids from a molecular viewpoint.

In this course, the macroscopic treatment of transport phenomena learned in previous courses is developed from molecular-level descriptions of matter. It is shown that the ad-hoc assumptions made in previous transport phenomena courses can be replaced by rational and scientific methods that will provide a general framework for the systematic analysis of complex systems or processes.

### COURSE OUTLINE AND DISCUSSION OF TOPICS

The outline of this one-semester course is given in Table 1, and a more detailed discussion of each
A section of material is given below. Suggested references in formulating the lecture for each section are also given.

**Mathematical Preliminaries**

Some mathematical preliminaries may be necessary, depending on the background of the students. Generally, students should have been exposed to some vector and tensor operations, such as summarized in Appendix A of Bird, Stewart, and Lightfoot. Additionally, some elementary concepts in probability are desirable. Our undergraduate students are exposed to such concepts in the second-semester engineering mathematics course. Regardless of the student backgrounds, however, I have found it important to review both of the above before proceeding with the core material.

**A. Introduction: Molecular View of Gases, Liquids, and Solids**

The purpose of this section of the course is to present a qualitative molecular picture of gases, liquids, and solids. Additionally, quantitative examples are given to illustrate the usefulness of a molecular interpretation of the three phases of matter.

An important dynamic feature of molecules is their seemingly random motion. The mechanical model shown in Figure 1 is a useful mechanical analog of the random motion of molecules. In this model, gravity causes the metallic balls to move down a cascade of inclined planes. When projected onto a screen, the balls appear to be under random molecular motion, as shown in Figure 2a. Of course, actual random motion is due to the collisions between molecules, where each molecule obeys Newton's Second Law of Motion.

The same mechanical model can also be used to provide a qualitative molecular picture of the three phases of matter. In a gas, the average intermolecular spacing is much greater than the diameter of a molecule or the average range over which intermolecular forces act; this is depicted in Figure 2a. In Figure 2b, a liquid is depicted by allowing all of the metallic balls to settle to the bottom of the container and then slightly tilting the container to one side. Although the intermolecular spacing is relatively small, there is a great degree of disorder in the molecular arrangements. This can be contrasted to a solid, shown in Figure 2c, where the container is tilted to an even greater angle. In solids, a regular arrangement of the molecules is observed and various types of packing geometries are possible.

In addition to the different geometric arrangement of molecules in gases, liquids, and solids, the trajectories or dynamics of the molecules are characteristically different. In Figure 3, adapted from Barker and Henderson, computer-generated trajectories of molecules (see section G below) in the three states of matter are shown. The tight spacing and strong molecular interactions in solids cause molecules to be constrained to move about fixed lattice sites in a seemingly vibration-type motion. In
liquids and gases, on the other hand, the spacing is not as close and the interactions are not as strong, and consequently the molecules have a less constrained motion.

The above discussions should lead to the recognition that the nature of the forces between molecules is important in determining the molecular picture and hence the properties of gases, liquids, and solids. A brief discussion of the Lennard-Jones potential is given in Bird, et al., although a more extensive discussion of intermolecular forces can be found.[8,9]

Although the above discussions are of a qualitative nature, some very simple, yet motivating, quantitative examples can be given that illustrate how the molecular picture can directly predict the observed macroscopic properties of matter. The following example, taken from Tabor,[10] illustrates the calculation of the internal energy change for sublimation of a crystal.

Example: The connection between molecular structure and macroscopic properties: The internal energy change for sublimation of an ionic solid.

The molecular structure of a NaCl ionic crystal is shown in Figure 4. In the process of sublimation, a change from the crystalline state to the vapor state takes place. Neglecting any subatomic contributions, the internal energy of the crystal is primarily due to the electrical potential energy associated with the configuration of the Na⁺ and Cl⁻ ions. Considering any ion in the crystal, we note that geometrically there are six nearest neighbors of opposite sign at a distance \( r \) from the ion, 12 neighbors of the same sign at a distance \( \sqrt{3} r \), 8 neighbors of opposite sign at a distance of \( 4/3 r \), etc.

According to Coulomb's Law, the total potential energy associated with moving each ion to its position relative to the central ion is

\[
U = \frac{1}{2} N \left( -\frac{6 e^2}{r} + \frac{12 e^2}{\sqrt{3} r} - \frac{8 e^2}{\sqrt{2} r} + \cdots - A \frac{e^2}{r} \right)
\]

where \( e \) is the electron charge and \( A \) is the so-called Madelung constant determined from the infinite series summation in Eq. (1) to three significant digits as 1.75.[10]

The above analysis is deficient in that other pair charge interactions have been overlooked, i.e., in bringing any charge to a specific location in the lattice, there will be Coulombic interactions with all other charges in the lattice and not just the central charge in Figure 4. Consider, for example, an ion located adjacent to the central ion in Figure 4. The potential energy of interaction in bringing it from infinity to its place on the lattice must include the pair interactions with all of its neighbors and not just the central ion. Because of the regular geometric arrangement of the lattice, however, the expression for the potential energy interactions for locating this ion is exactly the same as that calculated in Eq. (1) for the central ion. The total potential energy in constructing the lattice is, therefore, obtained by summing Eq. (1) over all ions in the lattice.

We are still not quite correct, however, in that we have counted all the pair interactions twice. If there are a total of \( N \) ions in the crystal, the total potential energy in constructing the lattice is finally given by

\[
U = \frac{1}{2} N \left( -\frac{6 e^2}{r} + \frac{12 e^2}{\sqrt{3} r} - \frac{8 e^2}{\sqrt{2} r} + \cdots - A \frac{e^2}{r} \right)
\]

Equation (2) represents a sum over pair interactions in the crystal, or "pairwise additivity." A general representation and discussion of pairwise additivity can also be given where Eq. (2) represents a special case for the NaCl ionic crystal.

In order to finally compute the internal energy change for the sublimation process, the internal energy of the NaCl vapor molecules is needed. Each NaCl molecule is a neutral molecule and, consequently, the total potential energy is obtained by multiplying the electrical potential energy associated with the formation of a single molecule by the total number of molecules, \( N/2 \). i.e.

\[
U_{\text{vapor}} = -\frac{1}{2} N \frac{e^2}{r_0}
\]

where \( r_0 \) is the interatomic distance for NaCl in the vapor state.

The internal energy change, per mole, for the sublimation process represents the difference in electrical potential energy between the vapor and solid states, which from Eqs. (2) and (3) is

\[
\Delta U_{\text{sub}} = \frac{1}{2} N_0 e^2 \left( \frac{1.75}{r} - \frac{1}{r_0} \right)
\]

where \( N_0 \) is the number of ions per mole. Using the values of \( r = (2.36 \times 10^{-10}) \text{ cm} \) and \( r_0 = (2.36 \times 10^{-8}) \text{ cm} \) given by Tabor,[10] the internal energy change for sublimation of NaCl crystal is calculated from Eq. (4) as 65.3 kcal/mole. An experimental value can be
estimated from heats of formation data as 54.7 kcal/mole, which is in good agreement with the calculated value.

Many other examples of this nature can be used to show the relationship between the molecular-level description of matter and macroscopically observed quantities. For example, Tabor also treats the problem of theoretically predicting the bulk modulus of a crystal from knowledge of the molecular interactions. These examples are very useful in motivating the molecular treatments of transport phenomena that follow in the remaining sections.

B. Transport Phenomena from Elementary Kinetic Theory

A simple, but elegant, treatment of the transport properties of gases can be shown through the elementary kinetic theory of gases. The so-called phenomenological laws of transport phenomena (Fick’s Law of Diffusion, Fourier’s Law of Heat Conduction, and Newton’s Law of Viscosity) are also derived through the elementary kinetic theory of gases. Consequently, this is a very useful introductory theory in establishing a firm physical foundation for discussing the phenomenological laws.

In general, mass, momentum, and energy can be transferred by a substance through random motions and interactions of its constituent molecules. This transfer takes place even in the absence of any overall or bulk-material motion. An everyday example is the rapid sensation of odors in a closed room, without drafts, at locations many meters away from the source of their emission. Here, random molecular motion is the driving force for a macroscopic transfer of material.

The phenomenon of macroscopic transfer as the result of random molecular motion is illustrated in Figure 5, which shows molecules of two different types, depicted as open and closed circles. The left-hand side of the plane at \( z = 0 \) is more concentrated in open circles than in closed, although the total number of circles is equivalent on both sides of the plane. One of the basic hypotheses of the elementary kinetic theory of gases is that a gas is comprised of molecules in constant random motion. Although this randomness is in all directions, for the sake of simplicity we will consider only one dimension. For example, consider random molecular motion in the \( z \)-direction, as shown by the arrows randomly affixed to each molecule in Figure 5. This could be accomplished by a series of coin tosses where a “heads” corresponds to an arrow pointing to the right, and a “tails” results in an arrow pointing to the left.

Over a small interval of time, several molecules will be transferred from the left-half to the right-half plane, and vice-versa, owing to random molecular motion, with the total number of molecules on either side of the plane remaining essentially unchanged (no overall motion). Because of the imbalance in concentrations, the several molecules transferred from the left-half to the right-half plane are predominantly open circles, whereas the several molecules transferred from the right-half to the left-half plane are predominantly closed circles. Thus, there will be a net transfer of open circles from a more concentrated region of open circles to a lower concentrated region of open circles. Likewise, the closed circles also are transferred from a region of high concentration of closed circles to a region of lower concentration of closed circles. Random molecular motion statistically tends to equalize concentration differences that exist in a system. The macroscopic observation is a net transfer of a molecular property in a direction from a high property concentration to a low concentration.

In addition to molecules being characterized as a certain type or species, molecules also possess the properties of momentum and energy. Since momentum is a vector quantity, there are three scalar components of momentum that are considered as separate properties. Gradients in the concentration of these properties (\( x, y, \) or \( z \) momentum/volume and energy/volume) will also result in a transfer of those properties through the system by random molecular motions.

There are many excellent quantitative developments of the elementary kinetic theory of gases that follow from the above qualitative description. A very concise quantitative treatment of the elementary

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*By macroscopic, we mean an observation made over a statistically large group of molecules.*
The purpose of this section is to develop the so-called Liouville equation, which is the starting point in the derivation of the transport equations and associated flux relations (see Section E below).

There are several introductory and clearly written developments of the Liouville equation that can be consulted for this section of the course, and only some highlights will be given here.

In this section and the remaining sections, we consider only molecules of a single type or species; the transport phenomena of multicomponent systems is beyond the scope of an introductory, one-semester course.

The first part of this section of material discusses the concepts of phase points and phase space. The phase point represents the collection of all momentum and position variables of the molecules in the system at any time. As the molecules move according to Newton’s Second Law of Motion, the phase point moves through a multidimensional space consisting of the momentum and position coordinates of all the molecules in the system. I have used simple cartesian coordinates in an undergraduate class. However, some instructors may wish to introduce the concept of generalized coordinates and Hamiltonian equations of motion.

Next, the concept of an ensemble of phase points is introduced. Each phase point or member of the ensemble initially consists of the same total number of molecules, same total momentum, and same total energy. There are, however, a number of different ways or realizations in distributing the initial positions and momenta of the molecules in order to achieve the same total values in energy and momentum (macroscopically indistinguishable systems). The collection of these realizations can be visualized as a “cloud” of phase points at any time. A number density function is introduced to quantify the “cloud” that moves through multidimensional space.

An analogy can immediately be drawn between the number density function for the phase points and the ordinary mass density function introduced in the first undergraduate transport course in fluid mechanics. In fact, the Liouville equation simply represents a conservation equation for the phase points as they move through multidimensional space.

I have used Figure 2.1 in Bird, et al., as a starting point in visualizing the development of the Liouville equation. An analogous figure can be thought of where a simple cube is replaced by a “hypercube” and the cartesian coordinates replaced by multidimensional coordinates (see Figure 6.4 of Reif). The rate of phase points entering the hypercube through any of the faces is simply the flux times the cross-sectional area (multidimensional in this case). The flux is simply the number density times the time rate of change of the coordinate normal to the face of the hypercube. Specific units are presented for both momentum and position coordinates to dimensionally verify that a “rate of phase points” is obtained for each term.

The final development involves substitution of Newton’s Second Law of Motion for each molecule and some simple reductions, although again generalized coordinates and Hamiltonian equations can be used for a more rigorous treatment. More discussion on the types of ensembles (microcanonical, canonical, etc.) could also be given at this time, but it is not necessary for the developments given below.

D. Reduced Distributions and Equilibrium Behavior of Matter

The Liouville equation derived in the previous section describes the behavior of the phase point number density function in a multidimensional space consisting of all momentum and position variables for the molecules in the system. Since the number of molecules in a system is typically very large (over a billion!), the solution of the Liouville equation represents a formidable problem. Fortunately, it will be shown in later sections that generally it is only necessary to know the behavior in a reduced space representing the positions and momentum of only a few molecules. Physically, this is because the interactions between molecules which lead to correlated behavior are generally of a short range and, thus, locally involve only a few molecules.

The phase point number density function, normalized with respect to the total number of members of the ensemble can also be interpreted as the probability of finding a member of the ensemble in a differential region of phase space. Below, this function is denoted as \( \rho(r^N, p^N, t) \) where \( (r^N, p^N, t) \) is shorthand notation for the multidimensional position and momentum coordinates \( (r_1, r_2, \ldots, r_N, p_1, p_2, \ldots, p_N, t) \). With this probability interpretation, the various types of reduced density functions and relationships between systems of distinguishable and indistinguishable molecules can be presented.

With the above preliminaries, the reduced form of the Liouville equation can be derived. The derivation requires the use of Green’s theorem and the
assumed "natural" behavior of the phase point number density function that it tends to zero as the position and momentum variables of the molecules tend to infinite values.

The configurational part of the reduced Liouville equation is useful in the development of equations of state and thermodynamic properties of gases, liquids, and solids. This equation can be derived as outlined by Hirschfelder, et al., and is recognized by statistical thermodynamicists as the "Integral Equation" for lower-ordered configurational distribution functions (see Section F below).

E. The General Equations of Change

It is the purpose of this section of the course to develop the transport equations (or mass, momentum, and energy conservation equations) from first principles. Although many introductory texts on kinetic theory and transport phenomena derive the transport equations beginning with the so-called Boltzmann transport equation (Section F below), following Irving and Kirkwood[15] we prefer to adopt a general approach and derive the transport equations directly from the Liouville equation developed in Section C. The resulting "General Equations of Change" are applicable to all types of flows, including laminar, turbulent, and shock flows, thus forming an important basis for understanding current and future developments in transport phenomena.

As mentioned in the previous section, the normalized phase point number density function \( \rho_N \) can be interpreted as a probability density function, i.e., \( \rho_N \, \mathrm{d}r^N \mathrm{d}p^N \) is proportional to the probability of finding a phase point in a multidimensional region between \((r^N, p^N)\) and \((r^N + \mathrm{d}r^N, p^N + \mathrm{d}p^N)\) at any time. Just as one defines the mean, variance, and other moments of probability density functions, we can also examine these quantities with respect to the phase point (probability) density function. More specifically, the averaging can be performed directly with the Liouville equation leading to the so-called transport equations. The transport equations thus represent the behavior of the various moments of the density function \( \rho_N \). These moments are defined more specifically below. Since the Liouville equation is a conservation equation, the transport equations also represent conservation equations for the various moments of the density function.

Following Irving and Kirkwood, the average or expectation value of any dynamical variable \( \alpha(r^N, p^N) \) that does not depend explicitly on time is introduced as

\[
E(\alpha) = \frac{1}{N!} \int \alpha(r^N, p^N) f_N(r^N, p^N, t) \, \mathrm{d}r^N \mathrm{d}p^N \tag{5}
\]

where \( f_N(r^N, p^N, t) = N! \rho_N(r^N, p^N, t) \) is the phase point density function for indistinguishable molecules.

A judicious choice of \( \alpha \) leads to the definitions of the average mass (or number) density, average momentum, and average energy for the fluid as follows:[15]

1) Average Total Mass Density, \( \rho(r, t) \)

\[
\alpha = m \sum_{k=1}^{N} \delta(r_k - r)
\]

where \( m \) is the mass of a single molecule and \( \delta \) is the Dirac delta function.

2) Average Total Momentum Density, \( \mathbf{v}(r, t) \)

\[
\alpha = m \sum_{k=1}^{N} \mathbf{p}_k \delta(r_k - r)
\]

3) Average Total Energy Density, \( \mathbf{U}(r, t) \)

\[
\alpha = \frac{1}{2m} \sum_{k=1}^{N} \mathbf{p}_k^2 \delta(r_k - r) + \frac{1}{2} \sum_{i=1}^{N} \sum_{j=1}^{N} \phi_{ij} \delta(r_i - r_j) \tag{8}
\]

Note that the first term in Eq. (8) represents the kinetic energy contribution, and the second term represents the intermolecular potential energy contribution.

The transport equations can now be derived using the simple paradigm of multiplying the Liouville equation by each of the defining relations for \( \alpha \) and integrating over all phase space. Since there are some similarities in each derivation, this process can be facilitated by first considering the conservation equation for \( \alpha \).[6,15] Generally, finding time to derive the energy balance equation has been difficult. For the purposes of this introductory course it is sufficient to derive the mass and momentum conservation equations and merely present the results for the energy conservation equation.

Finally, it should be noted that in the derivation of the transport equations, use is made of the integral relationship involving the derivative of the Dirac delta function[16,17]

\[
\int g(x) \delta^{(n)}(x - x_0) \, \mathrm{d}x = (-1)^n g^{(n)}(x_0) \tag{9}
\]

where \( \delta^{(n)} \) denotes the \( n \)th derivative of \( \delta \) with respect to \( x \) and, similarly, \( g^{(n)}(x) \) is the \( n \)th derivative of \( g \) with respect to \( x \) evaluated at \( x \). The derivation of Eq. (15) can be easily obtained by using one of the limiting definitions of the delta function (a generalized function) e.g., the limit of a normal or Gaussian density function as the variance tends to zero.

F. Transport Properties and Solutions to the Reduced Liouville Equation

The general equations of change derived in the previous section contained expressions for the property flux vectors representing the transfer of a property relative to the mass average velocity of the
fluid. It was shown that these expressions contain lower-order density functions whose behavior is dictated by the corresponding reduced forms of the Liouville equation introduced in Section C.

It is the goal of this section to show that various types of solutions to the reduced Liouville equation result in a form of the transport equations known as the Navier-Stokes equations. This derivation can be rigorously accomplished for dilute gases which, by definition, have at most only two molecule encounters; three or more molecule interactions are neglected. Consequently, the reduced Liouville equation derived in Section E can be truncated at order two for a dilute gas. From this truncated equation a very simple derivation of the so-called Boltzmann transport equation can be given.\(18\) Note that some discussion on the geometry and dynamics of a binary molecular collision is necessary in the development of the Boltzmann equation.

Having derived the Boltzmann transport equation, scaling and dimensional analyses are performed.\(19\) The Knudsen number, the ratio of a characteristic molecular length scale (such as the gas mean free path) to a characteristic macroscopic length scale, is introduced as an important dimensionless group for the Boltzmann transport equation.

By considering the two extremes (i.e., very small and very large Knudsen numbers), various approximate analytical solutions to the Boltzmann equation can be outlined. Unfortunately, there is not sufficient time in a one-semester course to cover these solutions in great detail. Typically, I have outlined the Chapman-Enskog solution to the Boltzmann equation, asymptotically valid at very small Knudsen numbers. This discussion includes the Boltzmann H-Theorem, the first-order perturbation expansion, and the general forms of the solutions. The overall presentation is sufficient to obtain the celebrated Navier-Stokes equation and the energy transport equation encountered in the students' previous courses on transport phenomena. Newton's Law of Viscosity and Fourier's Law of Heat Conduction are shown to naturally arise in the Chapman-Enskog solution method. The expressions for the coefficients of viscosity and heat conduction are also obtained. However, it is shown that further resolution of these expressions is needed (via solutions to a set of finite integral equations) in order to perform actual numerical calculations. Typically, there is not sufficient time to cover the solution to these specific integral equations, nor is it necessary at this level, and the final results can be presented without proof.

The above discussions and presentations are also sufficient for demonstrating the connection between thermodynamics and transport phenomena. It is readily shown that, under local equilibrium conditions, the normal component of the pressure tensor in a dilute gas is the thermodynamic pressure. For fluids that are far removed from local equilibrium, it is doubtful that the thermodynamic pressure can be utilized in a transport equation. Nonetheless, a general framework has been established for evaluating the pressure tensor in both equilibrium and nonequilibrium fluids; similar analyses can be applied to the evaluation of the internal energy.

A homework assignment can also be given that ties together thermodynamic and transport properties for dilute gases: experimental values of the second virial coefficients for a variety of dilute gases are used to determine the corresponding Lennard-Jones force constants.\(10\) The Lennard-Jones constants determined in this manner are, subsequently, used to predict the viscosity coefficients of each gas according to the Chapman-Enskog formula.

Some instructors may wish to present other solutions to the Boltzmann transport equation, such as Grad's 13-moment method; some recent reviews on solutions to the Boltzmann transport equation are given by Cercignani\(19\) and by Dorfman and van Beijeren.\(20\) A condensed discussion of the Chapman-Enskog method is given by McQuarrie\(21\) and a readable discussion is given by Vincenti and Kruger.\(22\)

G. An Introduction to Molecular Dynamic Computations

Given the dramatic advances in the scientific and engineering computational abilities provided by supercomputers and other machines, it is highly likely that many problems in transport phenomena will, in the future, be solved at the molecular level. It should be clear from the above discussions that the numerous approximations involved in actually resolving the transport equations limits the usefulness of the results for performing engineering calculations for a variety of different systems, other than systems of dilute gases. Although extending the usefulness of the statistical mechanical development of transport phenomena is a subject of current engineering and scientific research, molecular dynamics computations provide a fundamentally simple and rigorous means of studying transport phenomena for almost all classical fluids.\(1\)

There are many books and review articles on the molecular dynamics method. No attempt is made

\(1\) For a review of nonclassical or quantum mechanical methods for molecular dynamics, see Kosloff.\(20\)

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here to review the literature in this area. Rather, some suggested discussions and topics are given that are useful as further expositions of the topics covered in the previous sections. It is important that the students understand the basis and salient features of the molecular dynamics method and see the usefulness of the method in predicting equilibrium or nonequilibrium properties of matter.

A recent text by Heermann[23] discusses a number of important aspects of the molecular dynamics method, including finite difference schemes for solving the equations of motion for the molecules, periodic boundary conditions and minimum image convention, types of ensembles, and averaging methods for determining macroscopic properties. Heermann also lists a number of computer programs associated with the molecular dynamics method. For example, a clearly presented computer program listing is given for microcanonical (constant energy) ensemble equilibrium molecular dynamics. This program can be readily installed on a mainframe computer or network system. As an enlightening homework assignment,[23] the students can be asked to determine the equilibrium pair correlation function for a Lennard-Jones fluid discussed in Section D above. Comparisons between dilute gases, dense gases, and liquids can be made, as well as the study of other types of intermolecular potentials and equations of state.

Instructors may also wish to present other types of molecular dynamics methods or applications, including nonequilibrium molecular dynamics methods.[24] Because of the conceptually simple basis of molecular dynamics, instructors can have a great degree of flexibility (and fun!) in bringing their own interests into developing this part of the course.

CONCLUDING REMARKS

In general, I have found this course suitable as an upper-level chemical engineering elective course. A final student project is substituted in place of a final exam. The students can select any project that illustrates a molecular interpretation of the macroscopic properties of matter. Ideally, these topics should be taken from areas not fully treated in the lecture material, such as molecular design in solids, multicomponent systems, and other molecular dynamic or Monte Carlo simulation methods. Specific applications or potential applications to systems of interest to chemical engineering and related disciplines should be emphasized in the students’ projects. These additional topics could also be developed in a second-semester course where greater emphasis could be placed on molecular level engineering design of materials and processes.

Although the lecture material is taken from a number of different sources (a course text is currently in preparation), any introductory book on statistical mechanics or statistical physics, some of which are given in the references, should be used as a required supplementary text for the course. These texts can provide a source of homework problems and can be used as a basis for the development of some of the material suggested above.

REFERENCES

Award Lecture

COMPUTING IN ENGINEERING EDUCATION
From There, To Here, To Where?
Part 1: Computing

The ASEE Chemical Engineering Division Lecturer for 1990 is Brice Carnahan of The University of Michigan. The 3M Company provides financial support for this annual lectureship award, and its purpose is to recognize outstanding achievement in an important field of ChE theory or practice.

Brice earned his BS and MS degrees from the Case Institute of Technology (1955, 1956), and his PhD from the University of Michigan in 1965, all in chemical engineering. His doctoral research was on radiation-induced cracking of paraffins. Between 1959 and 1965, he worked closely with Professor Donald L. Katz, first as technical director of the Ford Foundation project Computers in Engineering Education and then as associate director of a follow-on NSF project, Computers in Engineering Design Education. He joined the faculty of the University of Michigan in 1965, where his research activities have focused on applied mathematics, modeling, digital computing, and development of software for computer-aided process analysis and dynamic simulation. He is coauthor of two Wiley Texts, Applied Numerical Methods and Digital Computing and Numerical Methods.

He and his colleague, Professor James Wilkes, are responsible for the required computing course for all freshmen engineering students at the University of Michigan, for which they have produced a steady stream of texts and instructional aids over the years.

Professor Carnahan was a founding member and first interim chairman of CACHE. He has subsequently served as CACHE vice-chairman and chairman, and is currently active as board member and publications chairman. He has held elected AIChE positions as CAST Division Director, Vice-Chairman, and Chairman, and is a member of the Editorial Board of Computers & Chemical Engineering.

Since the early 1980s, Professor Carnahan has been intimately involved with the planning, implementation, and management of the Michigan College of Engineering hierarchical, multivendor network, now incorporating over 2000 attached machines of widely varying power.

He has received numerous honors, including the University of Michigan's Distinguished Service Award (1974), the AIChE CAST Division Computers in Chemical Engineering Award (1980), the University of Michigan College of Engineering's Outstanding Teaching Award (1984), and the Detroit Engineering Society's Chemical Engineer of the Year Award (1989).

Notice of the 3M Lectureship award for 1990 came to me as a complete, though a very pleasant, surprise. Many chemical engineering academics have had greater impact on their specialties, including engineering computation. Nevertheless, I very much appreciate this singular recognition.

I would be remiss if I did not here acknowledge the special contributions of two Michigan faculty to my professional life and, indirectly, to this award. The first is Don Katz, one of the greats of 20th Century chemical engineering, who provided me at a young age with opportunity, responsibility, encouragement, and financial support for pursuing my interests in chemical engineering computing. He is sorely missed by all who knew him. The second is my colleague, Jim Wilkes, with whom I have worked and taught on an almost daily basis for the past thirty years. That sounds like a long time, but in fact, the years of our collaboration have passed all too quickly. They have been filled with much work, a sense of accomplishment, and lots of fun. Thanks, Jim. It's been great working with you. Here's to the future...and, yes Jim, I will work on that revision of Chapter 6...soon....

WHAT IS COMPUTING?

It is a bit disconcerting to be introduced as an "expert" on almost any topic, since the audience then expects the speaker to make the complicated simple, to provide clever insights into the nature of a phenomenon, or to predict the future accurately. It is especially onerous to be labeled a "computing" expert. The truth is that no individual can get a handle on more than a few small subspaces of what has become an enormous and amorphous computing universe, including, but not limited to:

1. Design and manufacture of hardware for symbolic (mostly numerical) operations, storage, display, and...
communication (e.g. networks)
2. Ancillary electronic equipment (e.g., sensors, a/d converters)
3. Software (e.g., operating systems) for hardware management, communication, and user interaction
4. A wide variety of procedural, object-oriented, and other tools for creating applications
5. Application programs for:
   • Creating and publishing documents
   • Organized storage and retrieval of information
   • Business and financial transaction/record keeping
   • Implementation of numerical and non-numerical algorithms
   • Engineering/scientific analysis, design, control, and simulation
   • Creation of graphical images
   • Visualization of computed results
   • Image analysis and pattern recognition
   • Integrating media (text, graphics, video, sound, TV) for education and entertainment
   • Knowledge-based tools predicated on rules and heuristics
   • Language, semantics, organization of the brain and human thought processes

Everyone, both lay and technically trained, is profoundly affected by "computing," but each of us has a private version of what computing is, based on our own limited experience (much like the elephant and the blind men).

I chose the lecture title primarily because this is a meeting of engineering educators, and few technological developments have had (and will in the future have) so pervasive an impact on engineering education and research as has digital computing. Unlike many important technological developments in the history of engineering, computing has not "matured" after fifty years of steady (often spectacular) advances. In fact, as we enter the last decade of this century, the pace of change is accelerating significantly in all of the areas listed above. The question mark in the title will let me end with some conjectures about current trends and the future.

Computing developments in engineering education have occurred by and large during my professional lifetime, starting in the mid-1950s. I would like to start from the perspective of a newly graduated (in 1955) chemical engineer, trace some of what I perceive as the most important computing developments over the past fifty years or so, and then make some predictions (guesses, really) about the future.

In fact, many of the computing tools used most by both students and faculty (e.g., word processors, data-base managers, spreadsheet programs, drawing and plotting packages, electronic mail and conferencing software) are essentially "non-technical"; of course, "technical" computing (involving large-scale programs for symbolic and numerical mathematics, analysis, design, and control) is also important to all of us some of the time, and I don't want to leave it out—I just want to take a broader view of what computing in engineering education is now and what it is likely to be in the future.

**THERE—THE EARLY YEARS**

Let's start with the "there" part of my title. "There" for me started when I graduated from Case Tech in 1955, within months of the introduction of the IBM 650, the first widely available commercial digital computer. That event passed without my knowledge. I had heard of (and seen, on television) the UNIVAC computer, mostly because of its use in tabulating and predicting the vote in the 1952 presidential election. The only computing device I had seen personally was an enormous unused mechanical analog integrator (covering perhaps two-hundred square feet of floor space) in the ME department at Case that had been used to solve some ODE's during World War II. The twelve-foot long K&E sliderule hanging on the wall of the same room looked a lot more useful to me. It was a prop for teaching new freshmen about fast and accurate calculation (three digits still isn't all that bad!). That giant rule, along with the dreaded drafting exercises (where were you, Claris CAD, when I needed you?), is retained vividly as part of my freshman memory.

I am surprised at how little most students (and faculty) know about the personalities and historical events that led up to the successful IBM 650 venture. Mention "light-bulb" and the response is "Edison"; "airplane" and the response is "Orville and Wilbur Wright"; "telephone" and the response is "Alexander Graham Bell"; "computer" and the response is (almost always) silence or (inaccurately) "IBM." Although many mechanical or electromechanical calculating machines were developed (very early by Pascal, late in the 19th Century by Burroughs and Hollerith, and during the first half of the 20th
Century by IBM and other companies), what most of us would call programmable digital computing developed along an essentially independent path, with ideas generated by a small number of clever, determined, and sometimes irascible, individuals. Table 1 shows a chronology of a few milestone events from the early history of digital computing.

Babbage,[1] who for a time held Newton's chair at Cambridge, is a tremendously interesting personality. His mechanical analytical engine incorporated the most important conceptual elements of the modern serial digital computer architecture, with the exception of the stored program. Much of what we know about Babbage's analytical engine stems from its promotion by Lady Ada Lovelace (hence the name for the programming language Ada), who was Lord Byron's daughter and a mathematician of some note. Babbage never got his engine to work, despite the expenditure of a great deal of his own money and earlier support from the British Admiralty (the first federal R&D proposal?). This failure was not caused by a flaw in his design, but because of his unusual management style and problems with accurate metal machining. Parts of his machine were built in the 1950s and are on display at the Science Museum in London (see Figure 1).

Nearly a century passed before Atanasoff designed the first all-electronic (vacuum tube) computational circuitry and built a special purpose digital computer at Iowa State University for solving twenty-nine (why twenty-nine is not clear) simultaneous linear equations. His work was interrupted by World War II, and his contributions are often slighted by historians. However, a recent thoroughly documented book[2] makes it clear that Atanasoff's contributions were substantial, and that they influenced the subsequent development of the ENIAC by Eckert and Mauchly at the University of Pennsylvania's Moore School.

The ENIAC was the first truly programmable digital computer; all programming was done manually with switches and cables. It was used for computing firing tables for the military, and its existence became public knowledge in 1946, after World War II. Some statistics: the machine was 100 feet long, 8.5 feet high, and several feet wide; it had twenty 10-digit registers in its arithmetic unit (each 2 feet long), and 18,000 vacuum tubes. An integer add required 200 microseconds, making it something like a 0.005 Mips (Million instructions per second) machine. The ENIAC (see Figure 2) was two to three orders of magnitude longer than today's computers!

In a classic 1946 paper,[3] Burks, Goldstine, and von Neumann first introduced the stored-program and other architectural concepts that appear in nearly

<table>
<thead>
<tr>
<th>Date</th>
<th>Machine • Description • Developer</th>
</tr>
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<tbody>
<tr>
<td>1833-1848</td>
<td>Analytical engine • mechanical general-purpose computer • Babbage at Cambridge and London</td>
</tr>
<tr>
<td>1939-1942</td>
<td>ABC linear equation solver • first all-electronic computational hardware • Atanasoff at Iowa State University</td>
</tr>
<tr>
<td>1944-1946</td>
<td>ENIAC (Electronic Numerical Integrator and Calculator) • first general-purpose electronic computer • Eckert and Mauchly at the University of Pennsylvania</td>
</tr>
<tr>
<td>1946</td>
<td>EDVAC (Electronic Discrete Variable Electronic Computer) • paper • stored program concept • Burks, Goldstine, and von Neumann at Princeton</td>
</tr>
<tr>
<td>1947-1952</td>
<td>Mark I, II, III, IV • electromechanical computers with separate data and instruction memories • Aiken at Harvard</td>
</tr>
<tr>
<td>1947</td>
<td>Whirlwind • special-purpose radar processor, first machine with core memory • MIT</td>
</tr>
<tr>
<td>1949</td>
<td>EDSAC (Electronic Delay Storage Automatic Computer) • first operating stored-program machine • Wilkes at Cambridge University</td>
</tr>
<tr>
<td>1950</td>
<td>BINAC • first American stored program computer • Eckert and Mauchly Co. for Northrup Aviation</td>
</tr>
<tr>
<td>1951</td>
<td>UNIVAC • first commercial computer (48 built) • Remington-Rand Corp.</td>
</tr>
<tr>
<td>1952</td>
<td>IBM 701 • first core-memory machine (19 built) • IBM</td>
</tr>
<tr>
<td>1955</td>
<td>IBM 650 • first high-volume computer (hundreds built), drum memory • IBM</td>
</tr>
<tr>
<td>1955</td>
<td>IBM 704 • first large scientific machine, first built-in floating point unit • IBM</td>
</tr>
</tbody>
</table>

Figure 1. Part of the mill (arithmetic unit) of Babbage's Analytical Engine, constructed after his death from original drawings. (British Crown Copyright, Science Museum, London)
all of our current (serial) computers; they called their machine the EDVAC. EDSAC, built by Wilkes at Cambridge University, was the first true stored-program machine built on the EDVAC model; it became operational in 1949.

The first American stored-program machine was the BINAC, built for Northrup Aviation by Eckert and Mauchly (who left the Moore School in 1947 to start their own company). It was fully functional by mid-1950 and served as the basis for the first commercial digital computer, the Remington-Rand UNIVAC, released in 1951; forty-eight UNIVAC systems were built, and the cost per machine was $250,000 (about $3 million in today's dollars).

IBM entered the digital computing business shortly after Remington-Rand, introducing its first computer, the IBM 701, in 1952; nineteen were built. The IBM 701 was the first stored-program machine to use truly random access magnetic core memory (previously developed at MIT in 1947 for a special-purpose radar signal processor called the Whirlwind).

At the same time, IBM was developing two other machines. One was a follow-on core-memory machine with the first built-in floating-point unit, the IBM 704; it was not really available in quantity until 1957-58. The second was a less expensive 'mass-market' computer, the IBM 650, with a magnetic drum memory. IBM eventually built several hundred of them, mostly for rental. The University of Michigan rented an IBM 650 in early 1956 to replace its mostly unsuccessful research computer with mercury delay line storage called the MIDAC (Michigan Automatic Digital Computer). The few who actually used MIDAC derisively said the acronym really stood for "Machine Is Down Almost Continuously." As I recall, the rental rate for the 650 was $35 per daytime hour (but only for hours when it was up!).

The presence of the new computer had nothing to do with my decision to go to Michigan for PhD work in the fall of 1956. I chose Michigan because it was one of the few schools with its own nuclear reactor, and I wanted to work with Joe Martin on a chemical/nuclear engineering problem. When I met with Joe for my first counseling session, he told me about the new University computer and that the mathematics department was offering a new course on digital computing, the first at Michigan. Once I was in that course (with about twenty other students) I knew that I wanted to be involved with computers far into the future (even though my research was to be unrelated to it). In fact, I became a teaching assistant in that first computing course the next term it was offered.

For those (most of you) who weren't around at that time, here is a picture of what students did during that first course offering:

• Each of us learned to operate the computer and then signed up for, at most, one hour at a time to solve our problems (I always ended up with the 2:00-3:00 AM slot!).
• The machine had no keyboard or printer—just a card reader and card punch. All communication was through punched cards or directly with keys on the console (the lights displayed information in bi-quinary format—you might want to look that one up!).
• All programming was in the machine's language; each instruction contained an operation code plus two addresses, one for an operand and another for locating the next instruction in the memory.
• The "operating system" consisted of a four-card machine-language loader. Program execution could be initiated, interrupted, or stepped one instruction at a time, directly from the console; the light pattern on the console was the only feedback available to the programmer/operator (the repeated light patterns from infinite loops were always fun to watch).
• The machine had a rotating-drum memory with fifty memory cells arranged in each of twenty 'cylinders' around the drum surface. Because of the time required for interpreting an instruction, retrieving the operand, and then processing the instruction, placement of both the data and the next instruction was critical for efficient execution. The location of each program instruction and data item on the drum had to be carefully considered, since a drum is not a random-access device.

How do you think a current student working on a Macintosh would respond to the following directions? If the instruction address is an even number, the data address should be three word positions later (on any cylinder) and the next instruction address should be four word positions beyond that. Since there are fifty word positions around the cylinder, the correct drum rotation angle for the next
instruction if 50.4 degrees. . . . If the instruction address is odd, the data address should be three word positions later and the next instruction address should be five positions beyond that, so the drum rotation angle for the next instruction is 57.6 degrees.

Not to worry—part-way through the course we began to use the GAT assembler, written by Graham, Arden, and Galler of the University of Michigan Computing Center. That helped a bit (symbolic names for operation codes and addresses) but still left the angle determination to the programmer. Then one day, late in the term, the SOAP assembler arrived...and life was never the same thereafter. The O in SOAP stood for "optimal," and the SOAP assembler took care of all those nasty angle details. After struggling with the machine's language, SOAP seemed nothing short of a miracle (I was amazed, like the monk in the XEROX ad).

I still have my programs from that course. The first was (you guessed it), "Find the volume of a cylinder, given the radius and height as data." I remember thinking that I could have done the whole thing on a slide rule in a tiny fraction of the time it took me to learn how to run the 650 and get the program working. But later in the course we were each asked to solve a problem of our own. I decided to solve the two-dimensional heat-conduction (Laplace) equation in an L-shaped section of a furnace wall. I can still remember the thrill of getting the program working—and not just working, but working with variable mesh sizes. It was my first exposure to the true power of the computer and of numerical methods.

For me, the computer die was cast!

**TRENDS IN COMPUTER PERFORMANCE**

In those very early days, it was clear to me that computers would get faster, more reliable, and less expensive—but not that they would get incredibly smaller, and orders-of-magnitude faster and cheaper (on a $/instruction or $/memory location basis). Data from the recent (already classic) text on computer architecture by Hennessy and Patterson on the relative performance of several classes of computers over the past twenty-five years or so is shown in Figure 3. The performance index is based on the time to completion of a mix of typical programs.

By and large, prices in current dollars of the various categories of machines have stayed fairly stable. Supercomputers typically cost many millions, mainframes sell for $500,000 to several million, minicomputers from $50,000 to $500,000, and microcomputers from $1,000 (minimal personal computers) to $75,000 (for high-performance workstations). Note that the rate of improvement in the performance index is undiminished over a twenty-five-year span and varies from about 18% per year for supercomputers to about twice that for microcomputers.

Figure 4 shows a different performance index for supercomputers and microprocessors that is particularly relevant to numerical engineering computations, MFLOPS (Millions of Floating-Point Operations Per Second). Although supercomputer processors still perform floating-point operations one to two orders-of-magnitude faster than the fastest current microprocessors, the message here is clear: the latest RISC (Reduced Instruction Set Computer) microprocessors (the middle curve) portend a rapid closure of the floating-point performance gap by relatively inexpensive microprocessors.

Figure 5 shows the rapid price/performance decreases over the past decade for DRAM (Dynamic Random Access Memory) chips used in computer
Fall 1991

### TABLE 2

<table>
<thead>
<tr>
<th>Year</th>
<th>Hardware/Software Milestone</th>
</tr>
</thead>
<tbody>
<tr>
<td>1960</td>
<td>ALGOL • Magnetic disks</td>
</tr>
<tr>
<td>1962</td>
<td>Time sharing (Dartmouth) • Virtual memory (ATLAS at Manchester)</td>
</tr>
<tr>
<td>1964</td>
<td>Pipelined processors (CDC 6600) • Microcoded processors, 32 bits, byte (IBM 360)</td>
</tr>
<tr>
<td>1965</td>
<td>Interactive graphics, Sketchpad (Sutherland)</td>
</tr>
<tr>
<td>1966</td>
<td>Multithreading • Minicomputer (DEC PDP/8) • Real-time computing</td>
</tr>
<tr>
<td>1967</td>
<td>Multithreading • Memory cache (IBM 360/85)</td>
</tr>
<tr>
<td>1969</td>
<td>Minicomputer (DEC PDP/11) • PASCAL</td>
</tr>
<tr>
<td>1970</td>
<td>UNIX</td>
</tr>
<tr>
<td>1971</td>
<td>4-bit Microprocessor (LSI-Intel 4004) • IBM 370</td>
</tr>
<tr>
<td>1972</td>
<td>Vector processor (CDC STAR)</td>
</tr>
<tr>
<td>1974</td>
<td>Personal (minicomputer) XEROX Alto), bitmapped display, mouse • Laser printer • Local Area Network (Ethernet)</td>
</tr>
<tr>
<td>1975</td>
<td>Object-oriented programming Smalltalk) • 8-bit microprocessor (Intel 8008)</td>
</tr>
<tr>
<td>1976</td>
<td>16-bit microprocessor (Texas Instrument 9000) • Supercomputer (Gray) • ARPANET • C</td>
</tr>
<tr>
<td>1977</td>
<td>Microcomputers (Apple II, TRS-80, PET)</td>
</tr>
<tr>
<td>1978</td>
<td>DEC VAX • Intel 8086 microprocessor</td>
</tr>
<tr>
<td>1979</td>
<td>Spreadsheets (VisiCalc) • Hayes Micromodem</td>
</tr>
<tr>
<td>1980</td>
<td>RISC processor (Berkeley, Stanford, IBM)</td>
</tr>
<tr>
<td>1981</td>
<td>Graphical user interface XEROX STAR) • IBM PC • DOS • Epson dot matrix printer</td>
</tr>
<tr>
<td>1982</td>
<td>Compaq portable • Cray 1M/2</td>
</tr>
<tr>
<td>1983</td>
<td>Apple Lisa • Gavilan laptop</td>
</tr>
<tr>
<td>1984</td>
<td>Macintosh • HP Laserjet printer</td>
</tr>
<tr>
<td>1985</td>
<td>Workstation (Apollo) • Desktop publishing (Postscript)</td>
</tr>
<tr>
<td>1986</td>
<td>IBM 3090 • Windows graphical user interface</td>
</tr>
<tr>
<td>1987</td>
<td>Sparc RISC processor (SUN workstation)</td>
</tr>
<tr>
<td>1988</td>
<td>Cray YMP (8 processors, 6 ns clock) • Convex, Alliant minisupercomputers • Stellar, Ardent, Silicon Graphics, graphics workstations • visualization • massively parallel processing (Connection machine) • OS/2</td>
</tr>
<tr>
<td>1989</td>
<td>Open Software Foundation (Standard UNIX)</td>
</tr>
<tr>
<td>1990</td>
<td>Superscalar RISC processor (IBM RS6000)</td>
</tr>
<tr>
<td>1991</td>
<td>ACE-MIPS RISC processor consortium • HP PA RISC processor • Apple-IBM agreement • Pen-based, notebook, handheld microcomputers</td>
</tr>
</tbody>
</table>

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**Figure 5. Costs of several generations of DRAM chips (data from Hennessy and Patterson[14]).**

Some long-range trends in computing equipment development are:

- **Performance growth** ranges from 18% per year for supercomputer processors to 35% per year for microprocessors.
- **Dynamic RAM chip element density** increases about 60% per year. 4-Mbit chips are now in mass production and IBM has announced plans to begin producing 16-Mbit chips. Hitachi has already fabricated a 64-Mbit chip in its laboratories.
- **Chip transistor count** increases about 25% per year, doubling every three years.
- **Hard disk bit density** increases about 25% per year, doubling every three years.
- **Hard disk access time** improves slowly (only 3 to 4% per year).

**PREDICTING THE FUTURE**

Who, in the late 1950s, would have guessed that national computer meetings that brought together a few hundred participants then would, only thirty years later, sometimes attract in excess of 100,000 attendees—and be held only in one or two dreadful places like Las Vegas and Anaheim for lack of room elsewhere? Who then could have guessed the scope of the computing business now?

Well, some did. I remember a talk by Thomas Watson, Jr., in 1959, at the dedication ceremony for the University’s new IBM 704. He predicted that by 1990, the computing business would be as big as the automobile business. That didn’t quite happen, as sales by the major computer companies are still substantially smaller than for the major auto manufacturers. Of course, had the car companies delivered performance improvements comparable to those for the products of the computing industry, we would all be driving $1 Ferraris across the continent in a few seconds, and car-company sales might not look so big (one disadvantage—the car would be very, very small!). If revenues from information-related businesses such as communication are added to those for the computing manufacturers, Watson’s prediction has probably already come true. In any event, it is certain to come true before the turn of the century. Oh, that I had had some investment cash in 1959!

What about other early predictions? In 1945, Vannevar Bush, inventor of the electronic analog main stores. Here the prices are in current (inflated) dollars. Note that for each chip category there is a similar pattern of a steep (nearly ten-fold) fall in prices as the chip goes into production and that the price cycles are almost identical despite the successive quadrupling of capacity.
computer at MIT and Director of the Office of Scientific Research and Development during World War II, postulated a future device that is clearly similar to the personal computer we (almost) all know and love. In an article entitled "As We May Think," he wrote:

The MEMEX will be for individual use, about the size of a desk, with display and keyboard that would allow quick reference to private records, journal articles, newspapers, and perform calculations.

Unfortunately, in 1967, in an article entitled "MEMEX Revisited," he wrote:

Will we soon have a personal machine for our own use? Unfortunately not!

How wrong he was, with the first microprocessor only a few years away. Of course, Vannevar Bush had apparently been wrong before. As a consultant, he is reputed to have advised IBM in the early 1950s that one-hundred IBM 650s would saturate the market, since they could do all the computing that the world needed done! (Could he have been right?)

After hearing many predictions over the years, I don't think that even the brightest are good at predicting the future of computing much beyond the next generation of hardware and software. This is not to be critical. Who among us in 1956 (slide rule hanging from belt) would have predicted that in 1990 I could buy a pocket calculator for $50 (in greatly inflated currency) that uses a procedure-oriented language, can retain several programs indefinitely, computes to at least eight-digit accuracy, and operates for months on end on a battery smaller than a dime?

THREE DECADES OF STEADY PROGRESS

Table 2 shows a chronology of major hardware/software developments during the past three decades, as I see them. I have verified most of the dates, but a few are from my own recollection and may be off by a year or two.

Having gone from "there" to "here" in the general categories of hardware and software, Table 3 shows several areas of chemical engineering where these technologies have had the biggest impact. Here I have not tried to arrange the list in strict chronological order.

Bob Seader (University of Utah) was the recipient of the 1990 Katz lectureship in our department. One of his two lectures was entitled "A Brief History of Computing in Chemical Engineering." His superb lecture covered the subject so well that I couldn't possibly improve on it here. A printed copy of Bob's lecture was sent to every chemical engineering department chairman last fall, and I highly recommend that you locate and read it. If you cannot find a copy, contact me and I will send one to you.

Editor's Note: The second half of this award lecture will be published in the next issue (Winter 1992) of CEE.

REFERENCES


Chemical Engineering Education
In their preface, the authors write that "... electrochemistry and electrochemical engineering as academic disciplines ... remain insufficiently taught at both undergraduate and post graduate levels." Their perspective is shared by others. The National Association of Corrosion Engineers (NACE) is currently forming a task group to find ways to improve corrosion education in this country. In spite of the fact that electrochemical systems encompass one-ninth of the chemical process industry, most chemical engineering undergraduates receive no exposure to the field beyond a two-week stint in a physical chemistry class. The authors express their hope that "this book will encourage many more teachers to take up the challenge of teaching an integrated applied electrochemistry course."

This text provides a compelling demonstration of the importance of electrochemical processes. In ten chapters and 460 pages the authors explore:

1. Electrolytic production of chlorine and caustic
2. Electrolytic extraction, refining, and production of metals through electrowinning, cementation, electrorefining, and electro-deposition of metal powders
3. Electrolytic production of a number of low-tonnage inorganic products such as fluorine, hydrogen peroxide, ozone, and manganese dioxide
4. Organic electrosynthesis of adiponitrile (used to make nylon) and other commercial electro-synthesis processes
5. Waste-water treatment by electrochemical processes such as electrodeposition of metal ions, in-situ formation of oxidizers, and electrodialysis
6. Metal finishing including electroplating, electroless plating, and electrophoretic painting
7. Metals processing, including electroforming and electrochemical machining and etching
8. Corrosion and corrosion control
9. Batteries and fuel cells
10. Electrochemical sensors and monitoring techniques

This text provides a broad overview of electrochemical technology, and the detail with which these systems are covered is sufficient for a survey course. The review of electrochemical practice is preceded by two chapters that cover the fundamentals of electrochemistry and electrochemical engineering. The discussion of fundamental electrochemical concepts (Chapter 1) is very compressed and may be tough going for the typical undergraduate chemical engineer. It does, however, outline the key factors that distinguish electrochemical processes from traditional chemical systems. The section on electrochemical engineering (Chapter 2) emphasizes costing of electrochemical processes and introduces typical cell designs.

This text could be used for an elective survey course directed to senior undergraduate students and beginning graduate students. The strength of the book, in this application, is its comprehensive overview of the field. The authors, however, do not make it easy for the instructor. The text does not include homework problems and, while general suggestions are made for further reading, specific attributions are not given for the material presented in the chapters. Therefore it is difficult to know precisely where to look for more information on a specific topic.

The discussion of fundamentals is not integrated into the discussion of industrial processes. While the authors stress the importance of current distribution in Chapters 1 and 2, such calculations are not employed for the design of industrial processes covered in Chapters 3 through 12. For example, the authors present different battery types in Chapter 11, but do not present the manner in which one would try to optimize the battery design based on principles governing current and potential distribution. Impressed current cathodic protection is presented in Chapter 10 as a means of controlling corrosion, but the equations used to design a cathodic protection system are not presented. This level of coverage is suitable for a survey course. For an advanced graduate-level class, I would want to apply the fundamental concepts by introducing the modeling and optimal design of some sample systems. \textit{Industrial Electrochemistry} could be an excellent complement to a text such as Newman'\textit{s Electrochemical Systems} in an advanced graduate course.

\textit{Industrial Electrochemistry} would be an excellent textbook for an upper-level undergraduate survey course on applied electrochemical technology.
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  Heterogeneous Catalysis • Kinetics • Polymerization

M. C. WILLIAMS, Ph.D. (University of Wisconsin)
  Rheology • Polymer Characterization • Polymer Processing

R. K. WOOD, Ph.D. (Northwestern University)
  Process Modeling and Dynamic Simulation • Distillation Column Control • Dynamics and Control of Grinding Circuits

For further information, contact
Graduate Program Officer, Department of Chemical Engineering
University of Alberta • Edmonton, Alberta, Canada T6G 2G6
PHONE (403) 492-3962 • FAX (403) 492-7219
THE UNIVERSITY OF ARIZONA  
TUCSON, AZ

The Chemical Engineering Department at the University of Arizona is young and dynamic, with a fully accredited undergraduate degree program and M.S. and Ph.D. graduate programs. Financial support is available through fellowships, government grants and contracts, teaching and research assistantships, traineeships and industrial grants. The faculty assures full opportunity to study in all major areas of chemical engineering. Graduate courses are offered in most of the research areas listed below.

- THE FACULTY AND THEIR RESEARCH INTERESTS -

MILAN BIER, Professor, Director of Center for Separation Science
Ph.D., Fordham University, 1950
  Protein Separation, Electrophoresis, Membrane Transport

HERIBERTO CABEZAS, Asst. Professor
Ph.D., University of Florida, 1985
  Statistical Thermodynamics, Aqueous Two-Phase Extraction, Protein Separation

WILLIAM P. COSART, Assoc. Professor, Assoc. Dean
Ph.D., Oregon State University, 1973
  Heat transfer in Biological Systems, Blood Processing

EDWARD J. FREEH, Adjunct Research Professor
Ph.D., Ohio State University, 1958
  Process Control, Computer Applications

JOSEPH F. GROSS, Professor
Ph.D., Purdue University, 1956
  Boundary Layer Theory, Pharmacokinetics, Fluid Mechanics and Mass Transfer in the Microcirculation, Biomechanics

ROBERTO GUZMAN, Asst. Professor
Ph.D., North Carolina State University, 1988
  Protein Separation, Affinity Methods

THOMAS W. PETERSON, Professor and Head
Ph.D., California Institute of Technology, 1977
  Combustion Aerosols, Hazardous Waste Incineration, Contamination in Micro-Electronics

ALAN D. RANDOLPH, Professor
Ph.D., Iowa State University, 1962
  Simulation and Design of Crystallization Processes, Nucleation Phenomena, Particle Processes

THOMAS R. REHM, Professor
Ph.D., University of Washington, 1960
  Mass Transfer, Process Instrumentation, Packed Column Distillation, Computer Aided Design

FARHANG SHADMAN, Professor
Ph.D., University of California-Berkeley, 1972
  Reaction Engineering, Kinetics, Catalysis, Coal Conversion, Advanced Materials Processing

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

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

DAVID WOLF, Visiting Professor
D.Sc., Technion, 1962
  Energy, Fermentation, Mixing

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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.

* Center for Separation Science is staffed by four research professors, several technicians, and several postdocs and graduate students. Other research involves 2-D electrophoresis, cell culture, electro cell fusion, and electro fluid dynamic modeling.
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
Torres, 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
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 • Biomedical 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
Shin, Kwang S., Ph.D., Northwestern • Mechanical Properties, High Temperature 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.
University of Arkansas
Department of Chemical Engineering

Graduate Study and Research Leading to MS and PhD Degrees

FACULTY AND AREAS OF SPECIALIZATION

Michael D. Ackerson (Ph.D., U. of Arkansas)
Biochemical Engineering, Thermodynamics

Robert E. Babcock (Ph.D., U. of Oklahoma)
Water Resources, Fluid Mechanics, Thermodynamics,
Enhanced Oil Recovery, Coal Gasification

Edgar C. Clausen (Ph.D., U. of Missouri-Rolla)
Biochemical Engineering, Process Kinetics

James L. Gaddy (Ph.D., U. of Tennessee)
Biochemical Engineering, Process Optimization

Jerry A. Havens (Ph.D., U. of Oklahoma)
Irreversible Thermodynamics, Fire and Explosion Hazards
Assessment, Dense Gas Dispersion

William A. Myers (M.S., U. of Arkansas)
Natural and Artificial Radioactivity, Nuclear Engineering

W. Roy Penney (Ph.D., Oklahoma State)
Process Engineering, Process Development, Fluid Mechanics

Thomas O. Spicer (Ph.D., U. of Arkansas)
Computer Simulation, Dense Gas Dispersion

Charles Springer (Ph.D., U. of Iowa)
Mass Transfer, Diffusional Processes, Safety and Loss
Prevention

Charles M. Thatcher (Ph.D., U. of Michigan)
Mathematical Modeling, Computer Simulation

Jim L. Turpin (Ph.D., U. of Oklahoma)
Fluid Mechanics, Biomass Conversion, Process Design

Richard K. Ulrich (Ph.D., U. of Texas)
Microelectronics Materials Fabrication and Processing

J. Reed Welker (Ph.D., U. of Oklahoma)
Risk Analysis, Fire and Explosion Behavior and Control,
Liquefied Gas Technology

FINANCIAL AID

Graduate students are supported by fellowships and
research or teaching assistantships.

FOR FURTHER DETAILS CONTACT

Graduate Program Advisor
Department of Chemical Engineering
3202 Bell Engineering Center
University of Arkansas
Fayetteville, AR 72701

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The University of Arkansas at Fayetteville, the flagship
campus in the six-campus system, is situated in the heart
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FACILITIES
The Department of Chemical Engineering occupies more
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- Catalysis
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- Interfacial Fundamentals
- Mass and Heat Transport
- Optimization
- Process Modeling and Identification
- Process and Control
- Process Simulation
- Process Synthesis
- Computer Aided Process Design
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For information and application write:
Dr. R.P. Chambers
Chemical Engineering
Auburn University, AL 36849-5127

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- Heat Transfer and Cryogenics
- Catalysis, Reaction Kinetics and Combustion
- Multiphase Flow in Pipelines
- Fluid Bed Reaction Systems
- Environmental Engineering
- Petroleum Engineering and Reservoir Simulation
- Enhanced Oil Recovery
- In-Situ Recovery of Bitumen and Heavy Oils
- Natural Gas Processing and Gas Hydrates
- Computer Simulation of Separation Processes
- Computer Control and Optimization of Bio/Engineering Processes
- Biotechnology and Biorheology

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For Additional Information Write

Dr. A. K. Mehrotra, Chairman • Graduate Studies Committee
Department of Chemical and Petroleum Engineering
University of Calgary • Calgary, Alberta, Canada T2N 1N4

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THE UNIVERSITY OF CALIFORNIA AT BERKELEY

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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
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SURFACE AND COLLOID SCIENCE
THERMODYNAMICS

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DEPARTMENT OF CHEMICAL ENGINEERING
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720

Fall 1991

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

The city of Davis is within easy walking or cycling distance to the campus. Both furnished and unfurnished apartments are available. Married student housing, as well as graduate dorms at reasonable cost, are located on campus.

Faculty & Research Areas


Dungan, Stephanie R., Massachusetts Institute of Technology. Structure & stability of food emulsions, intracellular transport, transport properties in microemulsions, interfacial dynamics.

Boulton, Roger, University of Melbourne. Chemical engineering aspects of fermentation & wine processing, fermentation kinetics, modeling & control of enological operations.


Jackman, Alan P., University of Minnesota. Biological kinetics & reactor design, kinetics of ion exchange, environmental solute transport, heat & mass transport at air-water interface, hemodynamics & fluid exchange.

Katz, David F., University of California, Berkeley. Biological fluid mechanics, biophysics, cell biology, image analysis.

McCoy, Ben J., University of Minnesota. Chemical reaction engineering - absorption, catalysis, multiphase reactors; separation processes - chromatography, ion exchange, supercritical fluid extraction.

McDonald, Karen A., University of Maryland, College Park. Distillation control, control of multivariable, nonlinear processes, control of biochemical processes, plant cell.


Phillips, Ronald J., Massachusetts Institute of Technology. Low Reynolds number hydrodynamics, suspension mechanics, hindered transport, transport in living plants.

Powell, Robert L., The Johns Hopkins University. Rheology, fluid mechanics, properties of suspensions & physiological fluids.


Smith, J.M., Professor Emeritus, Massachusetts Institute of Technology. Transport rates & chemical kinetics for catalytic reactors, studies by dynamic & steady-state methods in slurry, trickle-bed, single pellet, & fixed-bed reactors.

Stroeve, Pieter, Massachusetts Institute of Technology. Transport with chemical reaction, biotechnology, rheology of heterogeneous media, thin film technology, interfacial phenomena, image analysis.

Whitaker, Stephen, University of Delaware. Drying porous media, transport processes in heterogeneous reactors, multiphase transport phenomena in heterogeneous systems.

More Info

Information and application materials (including financial aid) may be obtained through the following address or telephone number.

Graduate Admissions Advisor
Department of Chemical Engineering
University of California, Davis
Davis, CA 95616
Telephone 916/752-2504; FAX 916/752-1031
CHEMICAL ENGINEERING AT

UCLA

FACULTY

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

PROGRAMS

UCLA's Chemical Engineering Department offers a program of teaching and research linking fundamental engineering science and industrial needs. The department's research strengths are demonstrated by its established centers of excellence in Hazardous Substances Control (NSF), Multimedia Environmental Pollution Studies (EPA), and Biotechnology Research and Education (NSF, State of California).

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

Located five miles from the Pacific Coast, UCLA's expansive 417-acre campus extends from Bel Air to Westwood Village. Students have access to the highly regarded 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
Particle Technology
Environmental Engineering

CONTACT

Admissions Officer
Chemical Engineering Department
5531 Boelter Hall
UCLA
Los Angeles, CA 90024-1592
(213) 825-9063

Fall 1991
FACULTY AND RESEARCH INTERESTS

L. GARY LEAL Ph.D. (Stanford) (Chairman) • Fluid Mechanics; Transport Phenomena; Polymer Physics.
SANJOY BANERJEE Ph.D. (Waterloo) • Two-Phase Flow, Chemical & Nuclear Safety, Computational Fluid Dynamics, Turbulence.
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.
JOHN E. MYERS Ph.D. (Michigan) (Professor Emeritus) • Boiling Heat Transfer.
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 PROFFIO Ph.D. (M.I.T.) • Biomedical Engineering, Reactor Physics, Radiation Transport Analysis.
ROBERT G. RINKER Ph.D. (California) • Chemical Reactor Design, Catalysis, Energy Conversion, Air Pollution.
ORVILLE C. SANDALL Ph.D. (U.C. Berkeley) • Transport Phenomena, Separation Processes.
P. 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 Phenomena, 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

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Professor Dale Pearson
Department of Chemical and Nuclear Engineering
University of California
Santa Barbara, CA 93106

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# Chemical Engineering

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## Faculty

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<th>Name</th>
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<td>Frances H. Arnold</td>
<td>Aerosol Science</td>
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<tr>
<td>James E. Bailey</td>
<td>Applied Mathematics</td>
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<tr>
<td>John F. Brady</td>
<td>Atmospheric Chemistry and Physics</td>
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<tr>
<td>Mark E. Davis</td>
<td>Biocatalysis and Bioreactor Engineering</td>
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<td>Richard C. Flagan</td>
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<td>George R. Gavalas</td>
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<td>Chemical Vapor Deposition</td>
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<td>Julia A. Kornfield</td>
<td>Combustion</td>
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<tr>
<td>Manfred Morari</td>
<td>Colloid Physics</td>
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<tr>
<td>C. Dwight Prater (Visiting)</td>
<td>Fluid Mechanics</td>
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<td>John H. Seinfeld</td>
<td>Materials Processing</td>
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<td>Nicholas W. Tschoegl (Emeritus)</td>
<td>Microelectronics Processing</td>
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<td>Zhen-Gang Wang</td>
<td>Microstructured Fluids</td>
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<td>Protein Engineering</td>
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<td>Statistical Mechanics of Heterogeneous Systems</td>
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for further information, write

Professor John F. Brady
Department of Chemical Engineering
California Institute of Technology
Pasadena, California 91125

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Clues

John L. Anderson
Membrane and colloid transport phenomena

Lorenz T. Biegler
Process simulation and optimization

Paul A. DiMilla
Cellular and biomolecular engineering; cell membranes

Michael M. Domach
Biochemical engineering and cell biology

Ignacio E. Grossmann
Batch process synthesis and design

William S. Hammack
Characterization of amorphous materials; pressure-induced amorphization

Annette M. Jacobson
Solubilization and surfactant adsorption phenomena

Myung S. Jhon
Magnetic and magneto-optical recording

Edmond I. Ko
Chemistry of solid-state materials; semiconductor processing

Gregory M. McRae
Mathematical modelling and public policy analysis

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

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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

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Faculty

Robert Jenkins
Yuen-Koh Kao
Soon-Jai Khang
Jerry Lin
Glenn Lipscomb
Neville Pinto
Sotiris Pratsinis

Amy Ciric
Joel Fried
Stevin Gehrke
Rakesh Govind
David Greenberg
Daniel Hershey
Sun-Tak Hwang

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- Material Synthesis
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- Membrane Separations
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- Polymers
  Thermodynamics, thermal analysis and morphology of polymer blends, high-temperature polymers, hydrogels, polymer processing.

- Process Synthesis
  Computer-aided design, modeling and simulation of coal gasifiers, activated carbon columns, process unit operations, prediction of reaction by-products.

For Admission Information

Director, Graduate Studies
Department of Chemical Engineering, #171
University of Cincinnati
Cincinnati, Ohio 45221-0171

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Dean of the Graduate School
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Charles H. Barron, Jr.  
John N. Beard, Jr.  
Dan D. Edie  
Charles H. Gooding  
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gas-solid and gas-liquid systems • optical techniques •
reaction engineering

Marvin Charles (Polytechnic Institute of Brooklyn)
biochemical engineering • bioseparations

John C. Chen (University of Michigan)
two-phase vapor-liquid flow • fluidization • radiative heat
transfer

Mohamed S. El-Aasser (McGill University)
polymer colloids and films • emulsion copolymerization •
polymer synthesis and characterization

Christos Georgakis (University of Minnesota)
process modeling and control • chemical reaction
engineering • expert systems

Dennis W. Hess (Lehigh University)
semiconductor and thin film processing

James T. Hsu (Northwestern University)
separation processes • adsorption and catalysis in zeolites

Arthur E. Humphrey (Columbia University)
biochemical processes • pharmaceuticals and enzyme
manufacturing • plant cell culture

Andrew J. Klein (North Carolina State University)
emulsion polymerization • colloidal and surface effects in
polymerization

William L. Luyben (University of Delaware)
process design and control • distillation

Janice A. Phillips (University of Pennsylvania)
biochemical engineering • instrumentation/control of
bioreactors • mammalian cell culture

Maria M. Santore (Princeton University)
dynamics of macromolecules at interfaces

William E. Schiesser (Princeton University)
umerical algorithms and software in chemical engineering

Cesar A. Silebi (Lehigh University)
separation of colloidal particles • electrophoresis • mass
transfer

Leslie H. Sperling (Duke University)
mechanical and morphological properties of polymers •
interpenetrating polymer networks

Fred P. Stein (University of Michigan)
thermodynamic properties of mixtures

Harvey G. Stenger, Jr. (Massachusetts Institute of Technology)
plasma etching • catalysis • air pollution control

Israel E. Wachs (Stanford University)
materials synthesis and characterization • surface chemistry
• heterogeneous catalysis
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.

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

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• 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

Fall 1991
DOUGLAS BOUSFIELD  Ph.D. (U.C. Berkeley)  
Fluid Mechanics, Rheology, Biochemical Engineering

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

JAMES D. LISIUS  Ph.D. (Illinois)  
Electrochemical Engineering, Composite Materials, Coupled Mass Transfer

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, Papemaking and Fiber Physics

• Faculty and Research Interests •

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. $17,000 Pulp and Paper Fellowships are available for qualified applicants.

• The University •

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

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Call Collect or Write •  James D. Lisius, University of Maine
Department of Chemical Engineering
Jenness Hall, Box B
Orono, Maine 04469-0135
(207) 581-2392

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

Facilities
The 6000 square feet of space dedicated to faculty and graduate student research includes state-of-the-art laboratory facilities. The BioProcess Scale-Up Facility on the College Park Campus is also available for use with classical microbial systems.

Faculty

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

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

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

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

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

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

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

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

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

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

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

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

College Park

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

Faculty:
William E. Bentley
Richard V. Calabrese
Kyu Yong Choi
Larry L. Gasner
James W. Gentry
Michael L. Mavrovouniotis
Thomas J. McAvoy
Thomas M. Regan
Theodore G. Smith
Nam Sun Wang
William A. Weigand
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)
P. R. Westmoreland, Ph.D. (M.I.T.)
H. H. Winter, Ph.D. (Stuttgart)
B. E. Ydstie, Ph.D. (London)

Current Areas of Research

- Combustion, Plasma Processing
- Process Synthesis, Design of Polymer and Solids Processes
- Statistical Thermodynamics, Phase Behavior
- Control System Synthesis, Adaptive Control
- 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

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

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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, Merck Pharmaceutical Manufacturing Division in West Point, Pennsylvania, and Chevron Corporation in Richmond, California, in addition to one or two semesters at MIT.

MIT is situated 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.

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
Chemical Engineering at
The University of Michigan

Faculty

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

For More Information, Contact:
Graduate Program Office, Department of Chemical Engineering / The University of Michigan / Ann Arbor, MI 48109-2136 / 313 763-1148
GRADUATE STUDY IN CHEMICAL ENGINEERING AT

MICHIGAN STATE UNIVERSITY

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

ASSISTANTSHIPS • Half-time graduate assistantships for incoming Master's candidates are expected to pay $13,500 per year net after all tuition and fees; the corresponding stipend for Ph.D. students is about $14,300. Theses may be written on the subject covered by the research assistantship.

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

• FACULTY AND RESEARCH INTERESTS •

D. K. ANDERSON, Chairperson
Ph.D., 1960, University of Washington
Transport Phenomena, Diffusion in Polymer Solutions

K. A. BERGLUND
Ph.D., 1981, Iowa State University
Sensors, Applied Spectroscopy, Food and Biochemical Engineering, Inorganic Polymers.

D. M. BRIEDIS
Ph.D., 1981, Iowa State University
Surface Phenomena in Crystallization Processes, Biochemical Engineering, Ceramic Powder Processing

C. M. COOPER, Professor Emeritus
Sc.D., 1949, Massachusetts Institute of Technology
Thermodynamics and Phase Equilibria, Modeling of Transport Processes

L. T. DRZAL
Ph.D., 1974, Case Western Reserve University
Surface and Interfacial Phenomena, Adhesion, Composite Materials, Surface Characterization, Surface Modification of Polymers, Composite Processing

H. E. GRETHELIN
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-Fruid 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, Radiotracer 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

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**Contact**

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

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**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

---

*Fall 1991*
The Faculty

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

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

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 • Corrosion

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

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

N. C. MOROSOFF (Ph.D., Brooklyn Tech)
• Plasma Polymerization • Membranes

P. NEOGI (Ph.D., Carnegie-Mellon)
• Interfacia Phenomena

G. K. PATTERSON (Ph.D., Missouri—Rolla)
• Mixing • Polymer Rheology

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

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

Fall 1991
The Department of Chemical Engineering, Chemistry and Environmental Science offers excellent opportunities for interdisciplinary research and graduate studies, particularly in the areas of hazardous waste treatment, materials science, and biotechnology. Both master's and doctoral degrees are offered in a growing program that has national and international research ties.

**RESOURCES**
- 20,000 square feet of modern laboratory and computing facilities
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- Major research facilities in hazardous substance management and microelectronics fabrication

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

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

For program information, contact:
Dr. Basil C. Baltzis, Graduate Advisor
Department of Chemical Engineering, Chemistry and Environmental Science
201-596-3619

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

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Research Areas

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

Faculty

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

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

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

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

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

- Ruben G. Carbonell (Princeton)  
  Multi-Phase Transport Phenomena; Bioseparations; Colloid and Surface Science

- Rey T. Chern (NC State)  
  Structure-Property Relations of Polymers; Membrane Separations

- 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

- 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
Two-phase heat transfer, fluid mechanics

Wesley R. Burghardt
Polymer science, rheology

John B. Butt
Chemical reaction engineering

Stephen H. Carr
Solid state properties of polymers

Buckley Crist, Jr.
Polymer science

Joshua S. Dranoff
Chemical reaction engineering, chromatographic separations

Thomas K. Goldstick
Biomedical engineering, oxygen transport in the human body

Harold H. Kung
Kinetics, heterogeneous catalysis

Richard S. H. Mah
Computer-aided process planning, design and analysis

William M. Miller
Biochemical engineering

Lyle F. Mochros
Biomedical engineering, fluid mechanics in biological systems

Julio M. Ottino
Fluid mechanics, chaos, mixing in materials processing

E. Terry Papoutsakis
Biochemical engineering

Mark A. Petrich
Environmental engineering, electronic materials, applications of solid state NMR

Gregory Ryskin
Fluid mechanics, computational methods, polymeric liquids

Wolfgang M. H. Sachtler
Heterogeneous catalysis

John M. Torkelson
Polymer science, membranes

M. Grae Worster
Fluid mechanics, convective heat and mass transfer

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Director of Graduate Admissions
Department of Chemical Engineering
Northwestern University
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- 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
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- Transport Phenomena

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- Robert S. Brodkey, Wisconsin 1952, Turbulence, Mixing, Image Analysis, Reactor Design, and Rheology
- Jeffrey J. Chalmers, Cornell 1988, Biochemical Engineering, Protein Excretion and Production, and Immobilized Cell Reactor Design
- L. S. Fan, West Virginia 1975, Fluidization, Chemical & Biochemical Reaction Engineering, and Mathematical Modeling
- Morton H. Friedman, Michigan 1961, Biomedical Engineering, and Hemodynamics
- Harry C. Hershey, Missouri-Rolla 1965, Thermodynamics, and Drag Reduction
- L. James Lee, Minnesota 1979, Polymer Processing, Polymerization, and Rheology
- Umit Ozkan, Iowa State 1984, Heterogeneous Catalysis and Reaction Kinetics
- James F. Rathman, Oklahoma 1987, Interfacial Phenomena, Surfactant Science, Rheology of Surfactant Systems
- Thomas L. Sweeney, Case 1962, Air Pollution Control, Heat Transfer, and Legal Aspects of Engineering
- Shang-Tian Yang, Purdue 1984, Biochemical Engineering and Biotechnology, Fermentation Processes, and Kinetics
- Jacques L. Zakin, New York 1959, Drag Reduction, Rheology, and Emulsions

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- Process Control
- Multiphase Mixing and Mass Transfer
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- W.J. Russell Chen (Ph.D., Syracuse, 1974)
- Nicholas Dinos (Ph.D., Lehigh, 1967)
- Daniel A. Gulino (Ph.D., Illinois, 1983)
- W. Paul-Jepson, Chem (Ph.D., Heriot-Watt, 1985)
- B. Benne kendall, P.E. (Ph.D., Case Institute of Technology, 1956)
- Michael E. Prudich (Ph.D., West Virginia, 1979)
- Darin ridgeway, P.E. (Ph.D., Florida State, 1990)
- Kendree J. Sampson, P.E. (Ph.D., Purdue, 1986)
- Robert J. Savage, P.E. (Ph.D., Case Institute of Technology, 1948)

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Roger G. Harrison, Jr., Associate Professor. Chemical Engineering: • Production of proteins and peptides using recombinant DNA technology • Separation and purification of biochemicals • Enzyme reactions • Protein engineering • Drug delivery systems • Applications of biotechnology to waste treatment

Jeffrey H. Harwell, Associate Professor. 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 • Conformational 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

Mathias U. Nollert, Assistant Professor. Chemical Engineering: • Biomedical engineering • Cellular metabolism and transport • Fluid mechanics

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John F. Scamehorn, 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 waste heat energy conversion
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Biochemical Processes
Corrosion
Design
Fluid Flow
Gas Processing
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Heat Transfer
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Department of Chemical Engineering
158 Fenske Laboratory
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- protein engineering
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- CD Han Rheology, Polymer processing
- TK Kwei Polymer-polymer miscibility, Phase relationships in polymers
- JS Mijovic Polymer morphology, Fracture properties of polymers
- AS Myerson Crystallization, Mass transfer
- EM Pearce Polymer synthesis and degradation
- LI Stiel Thermodynamics, Properties of polar fluids
- EN Ziegier Kinetics and reactor design, Air pollution control
- WP Zurawsky Plasma polymerization, polymer adhesion

For more information contact:
Professor A.S. Myerson
Head, Dept. of Chemical Engineering
Polytechnic University
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- Biomedical Engineering
- Catalysis and Reaction Engineering
- Colloids and Interfacial Engineering
- Environmental Science
- Materials and Microelectronics Processing
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- Bioseparations
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- Heat transfer
- High temperature kinetics
- Interfacial phenomena
- Microelectronics manufacturing
- Multiphase flow
- Polymer reaction engineering
- Process control and design
- Separation engineering
- Simultaneous diffusion and chemical reaction
- Thermodynamics
- Transport Processes

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Elmar R. Atwicker  Ph.D., Ohio State
Georges Belfort  Ph.D., California—Irvine
B. Wayne Bequette  Ph.D., Texas—Austin
Henry R. Bungay, III  Ph.D., Syracuse
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Steven M. Cramer  Ph.D., Yale
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Morris H. Morgan, III  Ph.D., Rensselaer
Charles Muckenfuss  Ph.D., Wisconsin
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Sanford S. Sternstein  Ph.D., Rensselaer
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Peter C. Wayner, Jr.  Ph.D., Northwestern
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- 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)
- 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
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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
Computer-Aided Design, Super-Critical Extraction, Control

M. R. FEINBERG, Ph.D. 1968, Princeton
Complex Reaction Systems, Applied Mathematics

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

J. C. FRIENDLY, Ph.D. 1965, California (Berkeley)
Process Dynamics, Control, Heat Transfer

R. H. HEIST, Ph.D. 1972, Purdue
Nucleation, Aerosols, Ultrafine Particles

S. A. JENKHE, 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, Combustion and Gasification of Coal, Gas-Solid Reactions

J. H. D. WU, Ph.D. 1987, M.I.T.
Biochemical Engineering, Fermentation, Biocatalysis, Genetic and Tissue Engineering

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- Hybridoma, Plant, and Insect Cell Cultures
- Interdisciplinary Biotechnology
- Cellular Bioengineering
- Bioseparations

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  - Food Processing
  - Genetic Engineering
  - Protein Engineering
  - Immunotechnology
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  - Electrochemical Engineering
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For further information contact:

Professor J. H. Gibbons
Chairman, Chemical Engineering
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Faculty

J. A. Biesenberger (PhD, Princeton University)
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Colloid & Surface Science
Combustion
Crystal Structure & Properties
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Heat Transfer
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Liquid Crystalline Polymers
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Membrane Science
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Ronald L. Fournier, Ph.D., University of Toledo. Associate Professor; Transport Phenomena, Thermodynamics, Mathematical Modeling and Biotechnology

Saleh Jabarin, Ph.D., University of Massachusetts; Physical Properties of Polymers, Polymer Orientation and Crystallization

James W. Lacksonen, Ph.D., Ohio State University. Professor; Chemical Reaction Kinetics, Reactor Design, Pulp and Paper Engineering

Steven E. LeBlanc, Ph.D., University of Michigan. Associate Professor; Dissolution Kinetics, Surface and Colloid Phenomena, Controlled Release Technology

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For Details Contact:
Dr. B. E. Poling, Chairman
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Toledo, OH 43606-3390
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M.S. and Ph.D. Programs in Chemical and Biochemical Engineering

RESEARCH AREAS

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Kenneth A. Debelak (Ph.D., Kentucky)
Artificial intelligence in process control; coal conversion with emphasis on particle structure and diffusional processes; hazardous waste minimization.

Tomlinson Fort (Ph.D., Tennessee)
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Todd D. Giorgio (Ph.D., Rice)
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Thomas M. Godbold (Ph.D., North Carolina State)
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David Hunkeler (Ph.D., McMaster)
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John A. Roth (Ph.D., Louisville)
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Karl B. Schnelle, Jr. (Ph.D., Carnegie Mellon)
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Eva M. Sevick (Ph.D., Carnegie Mellon)
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Robert D. Tanner (Ph.D., Case Western Reserve)
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For further information:
Professor Eva M. Sevick
Chemical Engineering Department
Box 1604 Station B
Vanderbilt University
Nashville, TN 37235
1-800-288-7722
University of Virginia
Graduate Studies in
Chemical Engineering

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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

FURTHER INFORMATION
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Biomaterials  
Colloids and Microemulsions  
Electrochemistry  
Fluid Mechanics and Rheology  
Interfacial Phenomena  
Mathematical Modeling  
Polymer Composites  
Process Control  
Reaction Engineering  
Surface Science
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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 online optimization of biochemical processes, adaptive control, drying of food products

J. C. Sheppard (Ph.D., Washington University): radioactive wastes, actinide element chemistry, atmospheric chemistry, radiocarbon dating

W. J. Thomson (Ph.D. University of Idaho): kinetics of solid state reactions, sintering rates of ceramic and electronic material precursors, chemical reaction engineering

B. J. Van Wie (Ph.D., University of Oklahoma): kinetics of mammalian tissue cultivation, bio-reactor design, centrifugal blood cellular separations, development of biochemical sensors

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J. T. Gleaves    Heterogeneous Catalysis, Surface Science, Microstructured Materials
J. L. Kardos    Composite Materials and Polymer Engineering
B. Khomami      Rheology, Polymer and Composite Materials Processing

J. M. McKelvey  Polymer Science and Engineering
R. L. Motard    Computer Aided Process Engineering, Knowledge-Based Systems
P. A. Ramachandran Chemical Reaction Engineering
R. E. Sparks    Biomedical Engineering, Microencapsulation, Transport Phenomena
C. Thies        Biochemical Engineering, Microencapsulation
M. Underwood   Unit Operations, Process Safety, Polymer Processing

For Information Contact
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<td>3 cr hrs Project II, Industrial Internship on project, full-time work</td>
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<tr>
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<td>3 cr hrs Technical Communication</td>
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<tr>
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<td>3 cr hrs Project III, write up thesis, possible part-time work</td>
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**call or write**

Dr. Ed Crum  
Chemical Engineering Department  
West Virginia Institute of Technology  
Montgomery, WV 25316  
(304) 442-3163

Dr. Bill Crockett  
School of Engineering and Science  
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Separation Processes
Surface and Colloid Phenomena
Phase Equilibria
Fluidization
Biomedical Engineering
Solution Chemistry
Transport Phenomena
Biochemical Engineering
Biological Separations

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Professor Richard Turton
Graduate Admission Committee
Department of Chemical Engineering
P.O. Box 6101
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Faculty Research Interests

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Kevin L. Bray
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Douglas C. Cameron
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Thomas W. Chapman
Electrochemical reaction engineering

Camden A. Coberly
Hazardous waste management, process design, composite materials processing

Stuart L. Cooper
Polymer structure-property relations, biomaterials

E. Johansen Crosby
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Juan de Pablo
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James A. Dumesic
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Charles G. Hill, Jr. (Chairman)
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Sangtae Kim
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Daniel J. Klingenberg
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James A. Koutsky
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Thomas F. Kuech
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Stanley H. Langer
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E. N. Lightfoot, Jr.
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Regina M. Murphy
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W. Harmon Ray
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Thatcher W. Root
Surface chemistry, catalysis, solid-state NMR

Dale F. Rudd
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Warren E. Stewart
Reactor modeling, transport phenomena, applied mathematics

Ross E. Swaney
Process synthesis and optimization, computer-aided design

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- Bioseparations

**Catalysis and Reaction Engineering**
- Adsorption and Transport in Porous Media
- Heterogeneous and Homogeneous Catalysis
- Zeolite Catalysis

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- **D. DiBiasio** • Ph.D., Purdue University
- **A. G. Dixon** • Ph.D., Edinburgh University
- **Y. H. Ma** • Sc.D., Massachusetts Institute of Technology
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Chemical Engineering Department
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