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Chemical Engineering Education
Department of Chemical Engineering
University of Florida
Gainesville, FL 32611
FAX 904-392-0861

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A Course in . . .

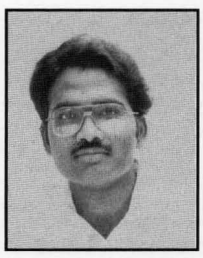
APPLIED BIFURCATION THEORY

VEMURI BALAKOTAIAH
University of Houston
Houston, TX 77204-4792

Bifurcation theory deals with the solution of nonlinear equations and is useful to chemical engineers studying nonlinear phenomena. Most of the traditional courses on applied mathematics offered by chemical engineering departments cover only linear analysis. While linear analysis is necessary, since it is the foundation of all nonlinear techniques, it does not prepare students to deal with the nonlinear problems that will be encountered later in research. This is especially true for students working on stability problems in fluid flow, heat and mass transfer, catalysis, reaction engineering, control, and separations.

For many years we have sent our University of Houston students to the mathematics department for courses on differential equations and dynamical systems, bifurcation theory, nonlinear dynamics, singularity theory, and group theory. We found, however, that many of these courses were too specialized, were abstract, and had a narrow focus (from an engineer's point of view). Typically, a student had to take three or four of these courses to grasp a few useful nonlinear techniques.

To address these problems, in 1989 the author designed a new course on applied bifurcation theory as a sequel to the two-semester applied mathematics course taught by Professor Neal R. Amundson. The course was well-received by the students and was repeated in the Spring of 1991, and with some minor changes and updating is scheduled to be taught in the Spring of 1994 and regularly thereafter.



Vemuri Balakotaiah *is professor of chemical engineering at the University of Houston. He received his BTech degree from the Indian Institute of Technology (Madras) in 1978 and his PhD from the University of Houston in 1982, both in chemical engineering. He worked as a Research Engineer at Shell Development Company and is a consultant to Exxon, Shell, and the Western Company of North America. His main research interests are in the area of chemical reaction engineering.*

COURSE DESCRIPTION

Introduction to Applied Bifurcation Theory

The main goal of the course is to expose chemical engineering graduate students to some important nonlinear techniques and concepts. Table 1 gives an outline of the material that is covered in a fourteen-week semester. Although the course is for 3 credits, 28 two-hour lectures are necessary to cover the topics listed in Table 1.

The course is organized into six topics and two introductory lectures. The introductory lectures give a brief history of bifurcation theory, examples from various disciplines, and the usefulness and limitations of bifurcation theory. Several chemical engineering examples covering fluid flow, heat and mass transfer, catalysis and reaction engineering, separations, control and multi-phase transport are selected as model problems and are used throughout the course to illustrate various concepts. All the examples are deterministic models and vary from the following simple (but non-trivial) two ordinary differential equation models

$$\frac{dx}{dt} = -\frac{x}{Da} + (1-x)\exp\left\{\frac{\theta}{1+\theta/\gamma}\right\} \tag{1a}$$

$$Le\frac{d\theta}{dt} = -\frac{\theta}{Da} + B(1-x)\exp\left\{\frac{\theta}{1+\theta/\gamma}\right\} - \alpha(\theta-\theta_c) \tag{1b}$$

describing the dynamic behavior of a CSTR in which a first order exothermic reaction occurs to the following, somewhat complicated, model involving a set of six partial differential equations in three spatial coordinates and time

$$\nabla\cdot\mathbf{v} = 0; \quad \nabla\Pi = -\mathbf{v} - \frac{Ra}{Pe_h}y\mathbf{e}_z \tag{2a}$$

$$\frac{\partial y}{\partial\tau} + \mathbf{v}\cdot\nabla y = \frac{1}{Pe_h}\nabla^2 y + \beta\,Da\exp\left(\frac{\gamma y}{1+y}\right)c \tag{2b}$$

$$\sigma\frac{\partial c}{\partial\tau} + \mathbf{v}\cdot\nabla c = \frac{1}{Pe_m}\nabla^2 c - Da\exp\left(\frac{\gamma y}{1+y}\right)c \quad (0<z,r<1, 0<\theta<2\pi) \tag{2c}$$

boundary conditions:

at the wall
$$\mathbf{v}\cdot\mathbf{e}_n = 0, \quad \nabla y\cdot\mathbf{e}_n = 0, \quad \nabla c\cdot\mathbf{e}_n = 0 \tag{2d}$$

at the inlet (z=0)
$$y = 0; \quad c = 1; \quad v_z = 1 \tag{2e}$$

at the exit (z=1)
$$\frac{\partial y}{\partial z} = 0; \quad \frac{\partial c}{\partial z} = 0; \quad \Pi = \Pi_1 \tag{2f}$$

describing flow maldistributions and hot spots in a down-flow cylindrical packed bed reactor. After a brief discussion of model formulation and the origins of various nonlinearities, we discuss the advantages of using the function space formalism. It is shown that most of the models can be written in the abbreviated form

$$\mathbf{C}\frac{d\mathbf{u}}{dt} = \mathbf{F}(\mathbf{u}, \mathbf{p}) \tag{3}$$

where $\mathbf{p}$ is a vector of parameters, $\mathbf{C}$ is a capacitance matrix, and the vector of state variables $\mathbf{u}$ may be expressed in terms of the elements of a function space having certain properties, *e.g.*, satisfying differentiability conditions and the appropriate boundary conditions. The function spaces of interest are usually Banach or Hilbert spaces. The capacitance matrix $\mathbf{C}$, the parameters vector $\mathbf{p}$, and the nonlinear operator $\mathbf{F}$ on the function space $\mathbf{Y}$ are identified for some selected examples. Some of these include cases in which $\mathbf{C}$ is not invertible (differential-algebraic systems). For example, for Eqs. (1),

$$\mathbf{C} = \begin{pmatrix} 1 & 0 \\ 0 & \mathrm{Le} \end{pmatrix}, \quad \mathbf{u} = \begin{pmatrix} x(t) \\ \theta(t) \end{pmatrix}, \quad Y = {}^{2}, \quad \mathbf{p}^{t} = (\mathrm{Le}, \gamma, B, \mathrm{Da}, \alpha, \theta_c) \tag{4a}$$

and

$$\mathbf{F}(\mathbf{u}, \mathbf{p}) = \begin{pmatrix} -\frac{x}{\mathrm{Da}} + (1-x)\exp\left\{\frac{\theta}{1+\theta/\gamma}\right\} \\ -\frac{\theta}{\mathrm{Da}} + B(1-x)\exp\left\{\frac{\theta}{1+\theta/\gamma}\right\} - \alpha(\theta-\theta_c) \end{pmatrix} \tag{4b}$$

while for Eqs. (2)

$$\mathbf{C} = \begin{pmatrix} \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & \sigma \end{pmatrix}, \quad \mathbf{u} = \begin{pmatrix} \mathbf{v}(z,r,\theta,t) \\ \Pi(z,r,\theta,t) \\ c(z,r,\theta,t) \\ y(z,r,\theta,t) \end{pmatrix}, \quad \mathbf{p}^{t} = (\mathrm{Ra}, \mathrm{Pe_h}, \mathrm{Pe_m}, \gamma, \beta, \mathrm{Da}, \sigma, \Pi_1, \alpha) \tag{5a}$$

$$\mathbf{F}(\mathbf{u}, \mathbf{p}) = \begin{pmatrix} \nabla\cdot\mathbf{v} \\ -\nabla\Pi - \mathbf{v} - \frac{\mathrm{Ra}}{\mathrm{Pe_h}} y\, \mathbf{e}_z \\ -\mathbf{v}\cdot\nabla y + \frac{1}{\mathrm{Pe_h}}\nabla^2 y + \beta\,\mathrm{Da}\exp\left(\frac{\gamma y}{1+y}\right)c \\ -\mathbf{v}\cdot\nabla c + \frac{1}{\mathrm{Pe_m}}\nabla^2 c - \mathrm{Da}\exp\left(\frac{\gamma y}{1+y}\right)c \end{pmatrix} \tag{5b}$$

TABLE 1
Course Outline for Applied Bifurcation Theory

Introduction

1. Definition and examples from different disciplines
2. Behavior of nonlinear systems; uses and limitations of bifurcation theory

Nonlinear Functional Analysis

1. Operators on Banach spaces; Fréchet derivatives
2. Contraction mapping theorem; iterative methods for nonlinear operator equations; uniqueness criteria
3. Implicit function theorem; necessary and sufficient conditions for bifurcation; determination of stationary stability boundary (Bifurcation Set)

Steady-State Bifurcation Theory

1. Liapunov-Schmidt reduction; elementary catastrophe theory
2. Singularity theory with a distinguished variable; classification of bifurcation diagrams; construction of phase diagrams
3. Effects of discrete symmetry (Z_2, D_3)
4. Shooting technique with sensitivity functions; determination of singular points of two-point boundary value problems; singular points of elliptic PDEs
5. Effects of symmetry on boundary value problems (Z_2, O(2))
   Branching equations with symmetries

Dynamical Systems

1. Invariant manifolds; Hartman-Grobman theorem; stable and center manifold theorems, applications
2. Amplitude equations; codimension 1, 2, 3 singularities
3. Poincaré-Birkhoff normal form; local codimention 1, 2 bifurcations
4. Floquet theory; degenerate Hopf bifurcations
5. Bifurcation theory for maps; normal forms of codimension one bifurcations ;attractors and basins of attraction
6. Poincaré maps; averaging method; Melnikov theory
7. Characterization of attractors ; attractor dimensions, K-entropy, L-exponents; analysis of experimental data
8. Poincaré-Bendixson theory; degree and index theory; group theory and normal forms; Hamiltonian chaos; fractals

Nonlinear Partial Differential Equations

1. Linear stability analysis of coupled PDEs
2. Center-manifold reduction of coupled PDEs; amplitude equations
3. Mode interactions; bifurcation with symmetry
4. Bifurcation in large systems (continuous spectrum); Landau and Ginzberg-Landau equations; phase and amplitude turbulence
5. Energy stability and Liapunov functions
6. Bifurcation theory for delay-differential, integral, and integro-differential equations

Nonlinear Wave Phenomena

1. Review of basic concepts; physical examples
2. Analysis of traveling waves and pulses

Computational Methods in Bifurcation Theory

1. Arc length continuation technique; continuation of steady-state and periodic branhces
2. Review of software on nonlinear dynamics and chaos

and **Y** is the space of 6-tuples of continuous functions in the variables (z,r,θ) satisfying the appropriate differentiability conditions and homogeneous boundary conditions.

Next, an overview of bifurcation theory, and its potential uses and limitations, are reviewed by a discussion of the following frequently asked questions about nonlinear models: 1) Given a nonlinear model of a physical system, what are the different types of behaviors that are possible (for different choices of the parameters vector **p**)? 2) What are the regions in the parameter space in which the behavior of a model may be described by a lower dimensional simplified model containing fewer parameters and/or a lower dimensional state space? What is the simplified form of the model? 3) How does one construct *phase diagrams* in the parameter space which classify the **p** space into regions, in each of which a different type of behavior exists? 4) How do the predicted features of a model change when it is subjected to small perturbations (or equivalently, is the model structurally stable)?

Theoretical, experimental, and computational results are presented for some model systems to illustrate each of the above four important concepts in some detail. For example, the idea of constructing a phase diagram of a mathematical model or a physical system is illustrated by using experimental results for Taylor-Couette flow[1] and theoretical results for the steady-state behavior of a CSTR.[2] It is also noted that phase diagrams for many of the model problems (including the two above) are not available.

The limitations of bifurcation theory are also discussed by emphasizing that its most important results are only local in nature and have to be supplemented by global techniques or numerical simulations (often guided by the local theory) for a comprehensive analysis of the mathematical model or physical system under consideration.

Main Topics of Applied Bifurcation Theory

We now give a brief description of the six main topics covered in the course. Before doing this, it should be pointed out that each of these topics (and most of the single lectures outlined here) is broad, has considerable literature, and finds enough applications in chemical engineering to justify a full semester course! As stated earlier, however, the purpose of this general course is to present the most important concepts and techniques in a unified manner. Due to space limitations, we must omit many details here. A longer version of this article containing details, equations, and commentary is available from the author.

Nonlinear Functional Analysis • The course starts with nonlinear functional analysis which introduces the notation and forms the basis for all later topics. First, the concept of completeness and convergence in normed linear (Banach) spaces is reviewed in a non-abstract manner. This is followed by the definition of a *Fréchet derivative* (or local linearization) of a nonlinear operator, chain rule, partial and higher-order Fréchet derivatives, and Taylor's theorem in function spaces. The model problems are used for illustration with formulas such as

$$D_{\mathbf{u}}\mathbf{F}(\mathbf{u}_0,\mathbf{p})\bullet\mathbf{v}=\frac{\partial}{\partial s}[\mathbf{F}(\mathbf{u}_0+s\mathbf{v},\mathbf{p})]_{s=0} \tag{6a}$$

$$D^2_{\mathbf{uu}}\mathbf{F}(\mathbf{u}_0,\mathbf{p})\bullet(\mathbf{v},\mathbf{w})=\frac{\partial}{\partial s_1}\frac{\partial}{\partial s_2}[\mathbf{F}(\mathbf{u}_0+s_1\mathbf{v}+s_2\mathbf{w},\mathbf{p})]_{s_1=s_2=0} \tag{6b}$$

for determining the Fréchet derivatives of the nonlinear operators (such as those in Eqs. 4b and 5b). Next, the concept of a nonlinear operator being a contraction is introduced and the contraction mapping theorem is stated. This theorem is used to present a proof of the implicit function theorem. The usefulness of these two main theorems of nonlinear functional analysis is shown by discussing various applications. For example, the contraction mapping theorem is used to derive convergence criteria for the iterative method

$$\mathbf{u}_{n+1}=\mathbf{N}(\mathbf{u}_n) \tag{7a}$$

as well as uniqueness criteria for the nonlinear equation

$$\mathbf{u}=\mathbf{N}(\mathbf{u}) \tag{7b}$$

where **N** is a nonlinear operator on some Banach space **Y**. Specific examples dealing with algebraic equations (lumped models of reactors with single and multiple reactions, discretized models of convection), two-point boundary value problems (diffusion-reaction and diffusion-convection-reaction models in one spatial dimension), and elliptic partial differential equations (diffusion-reaction models in 2/3 dimensions) are discussed. The implicit function theorem is supplemented by stating sufficient conditions for bifurcation and the form of the bifurcating solution in terms of the eigenfunctions of the linearized operator. Application of the implicit function theorem is illustrated by deriving the stationary stability boundaries for various physical systems such as the CSTR with single and multiple reactions, classical Rayleigh-Bénard and Lapwood convection problems, and the Brusselator model for stationary patterns.

Some lecture material on nonlinear functional analysis is taken from references 3 through 5 and 'translated' by the author into the engineer's language.

Steady-State Bifurcation Theory • The second topic of the course, steady-state bifurcation theory, is introduced by discussing the idea of reducing the dimensionality of a problem, also known as the elimination of passive modes (engineering), or the slaving principle (physics), or the Liapunov-

Schmidt reduction (mathematics). This is followed by a discussion of the branching equations and their Taylor expansions for finite dimensional problems and then is extended to infinite dimensional problems (Fredholm operators of index zero). For example, for the case of a single state variable bifurcation problem (characterized by dim ker $D_{\mathbf{u}}\mathbf{F}(\mathbf{u}_o,\mathbf{p}) = 1$), the branching equation is shown to be

$$g(x,\mathbf{p}) = \langle \mathbf{v}_1, \mathbf{F}(x\mathbf{y}_1 + \mathbf{W}(x\mathbf{y}_1,\mathbf{p}),\mathbf{p})\rangle \tag{8a}$$

where x is a scalar state variable (projection of the solution onto ker $\mathbf{L}^*$), and $\mathbf{y}_1,\mathbf{v}_1$ are the eigenfunctions corresponding to the zero eigenvalue of $\mathbf{L} = D_{\mathbf{u}}\mathbf{F}(\mathbf{u}_o,\mathbf{p})$ and $\mathbf{L}^*$ (adjoint operator), respectively. The function $\mathbf{W}(x\mathbf{y}_1,\mathbf{p})$ containing the slave variables (modes) is defined by the implicit equation

$$(\mathbf{I}-\mathbf{E})\mathbf{F}(x\mathbf{y}_1 + \mathbf{W}(x\mathbf{y}_1,\mathbf{p}),\mathbf{p}) = 0 \tag{8b}$$

where $\mathbf{E}$ is the projection operator onto the range of $\mathbf{L}$. Next, the main ideas of elementary catastrophe theory, such as *determinacy, transversality,* and *unfolding* are discussed, and Thom's classification and unfolding theorem is stated. The geometry of the elementary catastrophes (fold, cusp, swallowtail, butterfly, wigwam, and star) with the normal form

$$G(x,\varepsilon) = x^k - \sum_{i=0}^{k-2} \varepsilon_{i+1} x^i \qquad (k = 2,3,4,5,6,7) \tag{9}$$

and their bifurcation sets in the ε-space is discussed along with applications to lumped models of reactors and equations of state in classical thermodynamics.

The next lecture introduces singularity theory with a distinguished variable. First, the distinction between elementary catastrophe theory and singularity theory with a distinguished parameter is explained. For example, it is noted that the behavior of most physical systems is observed by measuring their response as a function of a distinguished physical parameter or variable (such as residence time, inlet temperature, etc.). In order to determine the different types of responses (bifurcation diagrams), it is necessary to rewrite the branching equation as

$$g(x,\lambda,\mathbf{p}^*) = 0 \tag{10}$$

where λ is the distinguished physical parameter and $\mathbf{p}^*$ is the vector of other parameters that are independent of λ. Next, the concepts of *contact equivalence, unfolding,* and *normal form* are discussed, along with a list of defining and nondegeneracy conditions for singularities up to codimension three. The different types of bifurcation diagrams that exist next to singularities of codimension one (hysteresis, isola, and double limit), codimension two (pitchfork), and codimension three (winged cusp) are reviewed. This is followed by a discussion of the method of constructing phase diagrams that divide the parameter space into regions with different types of bifurcation diagrams. The appearance and disappearance of solutions at the boundaries of the state variables and/or parameters is also discussed. The usefulness of the theory is illustrated by application to lumped models of chemical reactors.

The third lecture on steady-state bifurcation theory introduces the effects of symmetry. The occurrence of discrete symmetry is illustrated by giving physical examples with reflectional or Z_2 symmetry (two coupled identical cells and discretized models of convection) and permutational or D_3 symmetry (three coupled identical cells). Next, some important concepts of finite group theory such as *subgroup, group isomorphism, orthogonal representation,* and *irreducible representation* are discussed. The importance of these concepts is illustrated by discussing the invariance properties of kernel and range of $\mathbf{L}$ under the action of the group and the structure of the branching equations in the presence of these symmetries. This is followed by a statement of Thom's classification theorem for singularities with Z_2 symmetry and the geometry of the elementary catastrophes with this symmetry. The dihedral symmetry (D_3) is discussed, using the example of three coupled cells (simplest example where symmetry forces repeated eigenvalues).

The next lecture deals with the bifurcation analysis of two-point boundary value problems. First, it is shown that the Liapunov-Schmidt reduction for many nonlinear two-point boundary value problems (such as diffusion-reaction, convection-reaction, and diffusion-convection-reaction models in one spatial dimension) can easily be accomplished by using the shooting technique and sensitivity functions. The usefulness of this method is illustrated by deriving stability criteria (cusp locus) for the catalyst particle and the tubular autothermal reactor models. As the shooting technique is not applicable in higher dimensions, a procedure is presented for the determination of singular points of elliptic boundary value problems of the form

$$\mathbf{Lu} + \mathbf{N}(\mathbf{u},\mathbf{p}) = \mathbf{0} \quad \text{in } \Omega \quad (\mathbf{u} = \mathbf{0} \text{ on } \partial\Omega \text{ or } \nabla\mathbf{u},\mathbf{n} = 0 \text{ on } \partial\Omega) \tag{11}$$

where $\mathbf{L}$ has discrete spectrum with M zero eigenvalues, and $\mathbf{N}(\mathbf{u},\mathbf{p})$ is quadratic or higher order in $\mathbf{u}$. This problem is also used to illustrate the equivalence of the two main approaches to bifurcation theory, namely the Liapunov-Schmidt reduction and the perturbation (multi-scale) approach of Iooss and Joseph[6] using the Fredholm Alternative. The physical examples we discuss include problems of diffusion-reaction and diffusion-convection-reaction in higher dimensions consisting of a single or a pair of nonlinear elliptic partial differential equations with either Dirichlet, Neumann, or Robin boundary conditions.

The last lecture on steady-state bifurcation theory deals with the presence of symmetries in boundary value problems. First, examples of problems with reflectional (Z_2) and rotational symmetry (O(2)) are given (reaction-diffusion equations in a disk, ring, or line with Dirichlet or Neumann boundary conditions, problems of flow in pipes as well as artificially imposed periodic boundary conditions on physi-

cal systems). The presence of hidden symmetries (in the boundary conditions) is also illustrated. Next, the derivation of branching equations in the presence of Z_2 symmetry with single and double zero eigenvalue and O(2) symmetry with single (repeated) and double (repeated) zero eigenvalue is discussed. The occurrence of these bifurcations and the local bifurcation picture is illustrated by application to the buckling of a rectangular plate and the Brusselator model of pattern formation on a line and on a circular disk.

The lecture material on steady state bifurcation theory is taken from references 6 through 19, the author's thesis,[2] research publications, and notes.

Dynamical Systems • The third major topic, for which more than a quarter of the course is devoted, is bifurcation theory for ordinary differential equations. It begins with a review of the concept of asymptotic stability, the properties of hyperbolic fixed points, and the invariance of the generalized eigenspaces of the linear system with constant coefficients ($\mathbf{du/dt = Lu}$). This is followed by the linearization theorem of Hartman and Grobman for the local behavior of the nonlinear system

$$\mathbf{C}\frac{\mathbf{du}}{dt} = \mathbf{Lu} + \mathbf{N(u,p)};\quad \mathbf{N(0,p)} = \mathbf{D_u N(0,p)} = 0\quad \mathbf{u} \in \mathbf{Y} \subseteq R^n \qquad (12)$$

and the stable manifold theorem for a fixed point. Next, the slaving principle is explained in terms of the time scales (eigenvalues) associated with the eigenmodes and the Center Manifold theorem is stated. The usefulness of the Center Manifold theorem as a rigorous perturbation technique (that includes the classical regular perturbation/multiple-scale techniques) is illustrated by considering a two-phase model of a packed bed and deriving conditions under which it could be reduced to a single phase (pseudohomogeneous) model and the resulting model to infinite order!

The second lecture focuses on the application of Center Manifold theorem to reduce the dimension of the bifurcation problem defined by Eq. (12). First, a general procedure for determining the amplitude equations when **L** has r eigenvalues on the imaginary axis is presented (the nonlinear functional analysis and the notation are helpful in doing this in a compact manner). Specific results for the case of single zero eigenvalue, two and three zero eigenvalues, a pair of imaginary eigenvalues, and zero plus a pair of imaginary eigenvalues is presented. (Students are encouraged to verify and extend some of these formulas using symbolic manipulation.) For example, when a trivial solution exists for all values of the parameters vector **p** and there is a single zero eigenvalue at $\mathbf{p}_o$, it is shown that the amplitude equation to cubic order is given by

$$\frac{da_1}{dt} = a_i\left(\sum_{i=1}^{M} A_i\lambda_i\right) + Ba_1^2 + Ca_1^3 \qquad (13)$$

where $\lambda_i = p_i - p_{i0}$ (i=1,...,M) are the components of the parameters vector and p_{i0} are the parameter values at which there is a simple zero eigenvalue. The coefficients A_i, B, and C can be expressed in terms of some inner products involving the eigenvectors and adjoint eigenvectors of the linearized problem and higher order Fréchet derivatives of the function $\mathbf{F(u,p)}$.

The third topic of discussion is normal form theory, or equivalently, the transformation of the amplitude equations into their simplest form. First, it is shown that the calculation of the normal form of a set of amplitude equations involves near identity transformations and the solution of certain linear equations in polynomial vector spaces. Next, the normal forms (along with their universal unfoldings) are presented for some codimension one bifurcations (saddle-node and Hopf) and codimension two bifurcations (Takens-Bogdanov, zero, and a pair of imaginary eigenvalues and two pairs of imaginary eigenvalues) followed by a discussion of the local bifurcation behavior next to these singularities and the construction of phase diagrams in the unfolding parameter space. The application of the center manifold and normal form theories is illustrated using lumped models of chemical reactors (CSTR with single and multiple reactions) and discretized models of convection (Lorenz model and the five equation models of thermohaline and binary convection).

The fourth topic of discussion is Floquet theory and degenerate Hopf bifurcations. First, the general theory of linear systems with periodic coefficients, the method of calculation of the monodromy matrix, and the Floquet multipliers are reviewed. Next, the main theorem that gives the stability of the periodic solution in terms of the Floquet multipliers is stated. The two main degeneracies that may occur when Hopf's hypotheses break down are stated (coalescence of two Hopf points and the vanishing of the cubic coefficient in the normal form). The method of determining periodic solutions by analyzing the zeros of a nonlinear operator defined on the space of 2π-periodic functions is discussed. The Fitzhugh-Nagumo equations for nerve impulse, the Glycolytic model for oscillations, the Gray-Scott isothermal autocatalysis model, and the CSTR model are used for illustrating the construction of phase diagrams in the parameter space.

The next lecture is devoted to discrete dynamical systems. As in the case of continuous systems, the properties of hyperbolic fixed points and invariance of the generalized eigenspaces of the linear discrete system with constant coefficients ($\mathbf{u_{k+1} = Au_k}$) are reviewed. This is followed by the stable and center manifold theorems for the local behavior of the nonlinear system

$$\mathbf{u_{k+1}} = \mathbf{F(u_k,p)} = \mathbf{Au_k} + \mathbf{N(u_k,p)};\quad \mathbf{N(0,p)} = \mathbf{D_u N(0,p)} = 0 \qquad (14)$$

The calculation of the amplitude equations and the normal forms for codimension one bifurcations (saddle-node, transcritical, pitchfork, period doubling, and Naimark-Sacker) are illustrated. The different types of attractors (fixed points, periodic attractors, invariant circles, and strange attractors)

of discrete dynamical systems, the types of bifurcations that occur, the basins of attraction, and the fractal nature of the basin boundaries are illustrated using classical examples such as the logistic map, the delayed logistic map, the Hénon map, and the complex Newton iteration method for determining the fourth roots of unity.

The sixth lecture on dynamical systems is devoted to Poincaré maps, averaging methods, and Melnikov theory. First, the reduction of a continuous dynamical system to a discrete one through the Poincaré map and the method of construction of this map for three specific cases (near a periodic orbit, near a homoclinic orbit, and for a forced periodic system) as well as in the general case (using the method of Hénon) is illustrated. Next, the averaging theorem is used to obtain the Poincaré map for periodically forced dynamical systems using the forced Duffing equation as an example. At this stage, the dynamics of two-dimensional maps near homoclinic points is explained intuitively and the Melnikov method is presented for detecting the transverse homoclinic points. Chemical engineering examples discussed include periodically forced reactors and the dynamics of a gas bubble in a viscous liquid with periodic pressure variations.

The next lecture deals with the routes to chaos, definition and characterization of attractors, and the treatment of experimental data. First, the differences between the flows of conservative and dissipative dynamical systems is reviewed. Next, a strange attractor is defined and the three well-known routes to chaos are illustrated using the example of two coupled cells with the Brusselator kinetic scheme. Different methods for the analysis of experimentally (or numerically) generated time series are discussed. The calculation of attractor dimensions (using the method of Grassberger and Procaccia), Kolmogorov entropy, Liapunov exponents, and power spectra (using FFT) is illustrated with examples.

The last lecture on dynamical systems is a survey of various topics such as the global theory (Poincaré-Bendixson) of dynamical systems in the plane, degree and index theory, use of group theory to calculate normal forms, Hamiltonian chaos, and fractals. The lecture material on dynamical systems is taken from references 20 through 31 and research articles in *Physica D*. Examples and applications are taken from the author's notes.

Nonlinear Partial Differential Equations • The fourth major topic of the course is bifurcation theory for nonlinear partial differential equations. This topic is introduced with the method of linearization of Eq. (3) around some base state ($\mathbf{u}_o$), the solution of the system of linear partial differential equations

$$\mathbf{C}\frac{d\mathbf{v}}{dt} = \mathbf{L}\mathbf{v} = D_{\mathbf{u}}F(\mathbf{u}_o)\mathbf{v} \qquad (15)$$

and the properties of the eigenvalue problem ($\mathbf{Ly}=\mu\mathbf{Cy}$) and the adjoint eigenvalue problem $\left(\mathbf{L}^*\mathbf{v}=\bar{\mu}\mathbf{C}^*\mathbf{v}\right)$. Next, the two main theorems stating the necessary and sufficient conditions for simple and Hopf bifurcations are presented. Applications of the theorems are illustrated by physical examples such as Taylor-Couette flow, Rayleigh-Benard convection (principles of exchange of stabilities), Lapwood convection, and pattern formation on a catalytic disk (stationary/oscillating patterns).

The second lecture deals with the application of center manifold theory to partial differential operators in finite domains (discrete spectrum). Center manifold reduction of a system of PDEs and the derivation of the amplitude equations for M eigenvalues on the imaginary axis are illustrated. (The unified notation is again helpful as the same formulas are applicable for finite as well as for infinite dimensional problems, the only difference being in the summations.) The reduction of the Navier-Stokes equations for pipe and plane Poiseuille flows to an infinite set of coupled quadratic ODEs and the computation of the coefficients of the linear and quadratic terms in the amplitude equations are illustrated. Once again, the usefulness of the center manifold theorem as a generalized perturbation technique is shown by discussing a classical chemical engineering problem (Taylor-Aris dispersion) from a new perspective. (This example was taken from the joint work of the author with Professor Chia Chang, University of Notre Dame.)

The third topic of discussion is mode interactions in the presence of symmetries. The derivation of amplitude equations in the presence of two zero eigenvalues with Z_2 symmetry and two zero eigenvalues (repeated) and a pair of imaginary eigenvalues (repeated) with O(2) symmetry is illustrated along with the local bifurcation diagrams. The physical examples discussed include the problems of flow maldistributions in packed beds, reaction driven convection in a rectangular box, and stationary and moving temperature patterns on a circular catalytic disk.

The fourth lecture is devoted to the case of continuous spectrum (bifurcation in large systems). Here, the multiple scale perturbation technique combined with the Fredholm Alternative is used to derive the Landau (or the nonlinear heat) equation

$$\frac{\partial U}{\partial t} = \nabla^2 U + aU - bU^3 \quad (a,b \text{ real},\ U = \text{real amplitude}) \qquad (16)$$

for the case of continuous spectrum crossing the imaginary axis at zero and the Ginzburg-Landau (or the Newell-Whitehead-Segal) equation

$$\frac{\partial U}{\partial t} = U + (1+i\alpha)\nabla^2 U - (1+i\beta)|U|^2 U;\ \left(\alpha,\beta \text{ real}, U = \frac{\text{complex}}{\text{amplitude}}\right) \qquad (17)$$

for the case of complex continuous spectrum crossing the imaginary axis. The spatio-temporal patterns predicted by these equations and the concepts of phase and amplitude turbulence are briefly discussed.

The fifth lecture on PDEs is devoted to global techniques

such as Liapunov functions and energy stability theory. The classical Bénard problem is used to determine the stability boundary of the conduction state to finite perturbations (which coincides with the linear stability boundary). The example of through-flow in a porous medium is also used to illustrate the possibility of subcritical bifurcations predicted by energy stability theory. Finally, the construction of Liapunov functions is illustrated for some finite and infinite dimensional problems.

The last lecture is concerned with delay-differential, integral, and integro-differential equations (a topic that has applications in many areas of chemical engineering but is often ignored). The three examples include a system with time delay (Glass-Mackey model), a Fredholm integral equation of first kind with a symmetric kernel describing a diffusion-reaction problem, and an integro-differential equation describing the dynamics of a catalyst particle (with uniform internal temperature but non-uniform concentration gradients). These models show simple and Hopf bifurcations, period doubling, and chaotic behavior. For some of these cases, the local theory to compute the normal form is outlined.

The lecture material and examples on this topic are taken from References 10, 15, and 32 through 36, *Physica D,* and the author's research articles.

Nonlinear Waves • The fifth topic is nonlinear waves. Since the students are familiar with linear and hyperbolic (shock) waves covered in the applied mathematics course, some important concepts (such as phase velocity, group velocity, dispersion, and front steepening) are reviewed. Next, two chemical engineering examples (waves on a falling film and temperature waves on a catalytic wire or ribbon) are presented and some model wave equations, such as the long wave equation and the generalized Fisher's equation

$$\frac{\partial u}{\partial t} = \nu \frac{\partial^2 u}{\partial x^2} + f(u,\mathbf{p}) \tag{18}$$

are derived. The rest of the discussion is concerned with the wave properties of Eq. (18) and the nonlinear partial differential equation

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + \nu \frac{\partial^2 u}{\partial x^2} + \mu \frac{\partial^3 u}{\partial x^3} + \lambda \frac{\partial^4 u}{\partial x^4} = 0 \tag{19}$$

which includes as special cases some of the most widely studied equations, such as the Burger's equation ($\mu = 0$, $\lambda = 0$), the Korteweg-de Vries equation ($\nu = 0$, $\lambda = 0$), and the Kuramoto-Sivashinsky equation ($\mu = 0$). Substituting the traveling wave assumption

$$u(x,t) = h(z), \qquad z = x - ct \tag{20}$$

reduces Eq. (18) to a set of two ODEs (which can be analyzed by phase plane techniques) and Eq. (19) to a set of three ODEs which exhibit periodic, quasiperiodic, and chaotic solutions. The physical interpretation of these solutions as well as the variation of the wave speed with the parameters of the system are discussed.

The lecture material for this topic is taken from references 37 and 38, along with the author's notes.

Computational Methods • The last two lectures are devoted to computational methods in bifurcation theory. First, the arc length continuation technique as described by Kubicek and Marek[39] is presented. This is followed by a review of the software (such as DERPAR, AUTO2, etc.) for the continuation of steady-state and periodic branches. The recent software package KAOS of Kim and Guckenheimer is also reviewed and used by some students. It is also noted that there are very few algorithms available for computing bifurcation branches in the presence of symmetries. The lecture material for this topic is taken from references 39 and 40.

STUDENT PERFORMANCE

A set of fifty homework problems are given to the students after the introductory lectures and the students are asked to attempt five of them and submit a written report on one problem. More than half of these problems are open-ended and challenge the students (four of the problems later became topics of the students' PhD dissertations and led to several refereed publications).

A combined total of twenty-four students took the course for credit (and many others audited). In general, the students fell into two groups: those who were doing either experimental or theoretical research on nonlinear systems, and those who took the course to complete their graduate course requirements. The second group of students attempted straightforward homework problems such as computing the attractor dimensions or extending the Liapunov-Schmidt/Center Manifold calculations using symbolic manipulation. The first group of students attempted open-ended problems, but their solutions were incomplete (some were completed a few years later).

CONCLUSIONS

Linear analysis played a key role in the development of applied sciences during the nineteenth and first-half of the twentieth century. It is believed that nonlinear analysis combined with the power of the computer will play a similar role in the next century. The local nonlinear techniques of bifurcation theory extend the traditional linear analysis and are essential in the development of algorithms for computation. They also guide the search for solutions of nonlinear systems in multidimensional parameter spaces. The computer experiments play a complementary role and extend and validate the local theory

as well as lead to new and unexpected results (such as the discovery of the soliton). It is the author's opinion that some analysis and computational experience with nonlinear systems should be part of a standard training program for all graduate chemical engineers.

ACKNOWLEDGMENTS

The author is indebted to Professors Martin Golubitsky and Giles Auchmuty of the mathematics department at the University of Houston, with whom he has had many discussions on singularity, bifurcation, and group theories. This article was written while the author was on sabbatical leave at the University of Minnesota.

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ChE book review

ELEMENTS OF CHEMICAL REACTION ENGINEERING:

2nd Edition

by *H. Scott Fogler*

Prentice Hall, Englewood Cliffs, NJ (1992)

Reviewed by

P. R. Westmoreland

University of Massachusetts

The second edition of this text already comes about as close to universal usage as a chemical engineering text can, including wide international use in addition to 108 schools (in a recent count) in the U.S. It is not as well suited for graduate study, but (as far as I am concerned) it is the best undergraduate reaction engineering text available, based on its content, structure, and wide variety of good problems.

This edition, like the first edition did, covers the necessary subject territory of reaction engineering within its fourteen chapters:

Continued on page 166.

MOLECULAR LEVEL MEASUREMENTS IN CHEMICAL ENGINEERING

R. J. SMILEY, W. N. DELGASS
Purdue University
West Lafayette, IN 47907

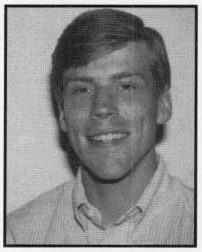
For quality control of a complex polymerization, or tracing the cause of poor paint adhesion, or understanding substandard performance of a catalyst batch, and for a host of other challenges, practicing chemical engineers may well find the greatest benefit by using a molecular level approach to the problem. While it is likely that the engineer will have to call on an expert to bring the full power of a given technique to bear on a given problem, it is important that he or she be sufficiently aware of the molecular-level tools available to begin asking the right questions.

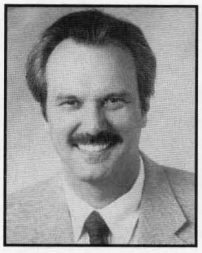
At Purdue, an elective course, called "Molecular Level Measurements in Chemical Engineering," for juniors, seniors, and graduate students, was designed to fill this need by sensitizing students to a variety of microscopic and spectroscopic characterization tools. Most students who graduate with a BS degree in chemical engineering have had only limited exposure to the characterization tools that will be available to them as professionals in industry or academia. Undergraduate engineering laboratory courses tend to focus on traditional chemical engineering equipment, and when chemistry laboratory courses use modern spectroscopic methods, they rarely make a connection to an engineering context. In our course, a brief discussion of the basic theory, instrument design, and sample requirements establishes the basic physics of the particular technique and the type of information it can give. Applications drawn from the literature illustrate the utility of the method in addressing engineering problems.

COURSE PHILOSOPHY

The course grew out of a conviction that chemical engineers can best extend their technical longevity through an understanding of the molecular basis of the properties and behavior of engineering materials and processes. To use this understanding, one must be able to make measurements on the molecular level.

R.J. Smiley *is a graduate chemical engineering student at Purdue University. He received his BS degree from Cornell University in 1989. His research interests focus on studying interfacial interactions of composite materials on the molecular level by X-ray photoelectron spectroscopy, electron microscopy, and scanning force microscopy.*





W. N. Delgass *is Professor of Chemical Engineering at Purdue University. He received his BS in chemical engineering from the University of Michigan, and his MS and PhD degrees from Stanford University. His research interests are in the kinetic and surface chemical characterization of solid catalysts and other advanced materials.*

The primary objective of the course is to introduce students to various tools that will extend their ability to solve problems. It is important to note that we stress that the course only *introduces* the various techniques and is not meant to make the students experts in a particular field. We have chosen breadth over depth to give students a wide scope of applications, but we try to include sufficient detail of some techniques to foster an appreciation of the care it takes to get the most information available.

The first of two secondary objectives of the course is the effective reading of technical papers. Our reliance on primary source material gives us an opportunity to emphasize critical evaluation of journal articles. Problem sets designed around current articles ask students to challenge and justify statements they read, to derive equations and discuss assumptions in the paper, and to consider what new or corroborating evidence might be obtained from alternative experimental approaches. For some students, these exercises provide the first recognition of the fallibility of the printed word and are, thus,

important steps in learning the winnowing process that is central to self-education.

Finally, we have incorporated laboratory exercises into the course that will at least *introduce* students to the hardware associated with advanced instrumentation. Each class day spent on an instrument limits the breadth of topics the course can cover, but the students confirm that *talking* about an experiment does not have the same impact as *doing* it. This past spring we included three lab periods to cover X-ray photoelectron spectroscopy, electron microscopy, and infrared and nuclear magnetic resonance spectroscopies.

COURSE DESCRIPTION

Table 1 gives the course outline. It begins with a brief overview of the techniques that will be covered in the class. Starting with the Propst diagram (see Figure 1) and the energy spectrum, we discuss the different ways of perturbing a sample with fields, photons, ions, neutrals, and electrons, and point out the types of information one might hope to learn.[1] Emphasis on applications shows where the course is heading and is intended to justify the need for the two-week review of background material that follows. Discussion of deBroglie's equation, the uncertainty principle, and Schrödinger's equation, together with derivations for a particle in a box and simple harmonic motion, and review of atomic and molecular orbital theory as well as some simple symmetry concepts provide the foundation on which all the molecular level techniques rest.

We begin quantitative surface analysis with a detailed discussion of X-ray photoelectron spectroscopy

TABLE 1
Outline of Major Topics

1. Introduction and Background (2 weeks)
- Propst Diagram
- Classical and quantum mechanics
- Symmetry

2. Quantitative Surface Analysis (4 weeks)
- X-ray photoelectron spectroscopy (XPS)
- Ion scattering spectrometry (ISS)
- Secondary ion mass spectrometry (SIMS)

3. Bulk and Surface Structural Analysis (4 weeks)
- Diffraction (XRD, LEED)
- Electron microscopy (TEM, SEM, AEM)
- Scanning probe microscopies (STM, SFM)

4. Chemical Characterization (4 weeks)
- Infrared spectroscopy (IR)
- Raman spectroscopy
- Nuclear magnetic resonance spectroscopy (NMR)
- Mass spectrometry (MS)

5. Case Studies (1 week)

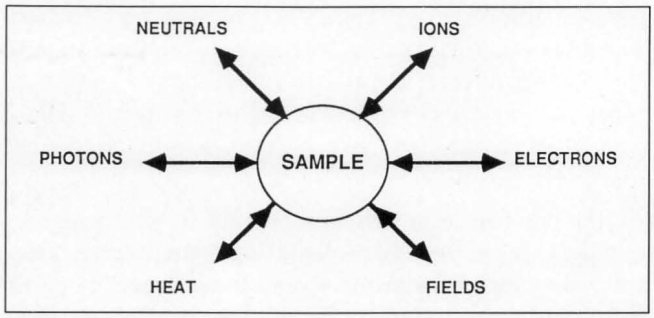


Figure 1. *The Propst Diagram. Arrows pointed inward represent various probes used to perturb the sample. Different responses to perturbation, indicated by the outgoing arrows, provide information about the sample.*

(XPS), including important features such as surface sensitivity, elemental and chemical state analysis, and quantitative capabilities. Detailed lectures focus on spectral interpretation by analysis of peak position, area, shape, and splitting.

In order to illustrate the potential of XPS, we spend several lectures discussing spectra from papers in the literature. One example of XPS analysis of the interactions between metal and metal oxide films shows students that surface properties are often much different from bulk properties, and that these differences directly affect the quality of the finished product.[2] These discussions are often the first time students are asked to extract information from spectra. Not surprisingly, they are initially reluctant to volunteer opinions, but we find that giving them the papers in advance and providing them with a few key questions to consider stimulates discussion.

After a relatively detailed presentation of XPS, we study Auger electron spectroscopy (AES), ion scattering spectroscopy (ISS), and secondary ion mass spectrometry (SIMS). Because much of the instrumentation and principles of XPS also apply to this next group of techniques, we move quickly through this part of the course to focus on applications of these tools.

The next section is on examination of bulk and surface structure by diffraction and microscopy. We begin this part of the course with a discussion of crystal structure and X-ray diffraction (XRD), electron diffraction, and low energy electron diffraction (LEED). Lectures are designed to compare and contrast the instrumentation as well as the information provided by each technique.

Scanning and transmission electron microscopies are introduced next. One class period is a laboratory demonstration of the potential of SEM and TEM for studying biological and structural materials. Before the laboratory session, we devote a lecture to

contrasting the two types of microscopes and explaining the differences in resolving power, instrument design, and sample requirements. Analytical tools such as energy dispersive X-ray analysis (EDX) and electron energy loss spectroscopy (EELS) are also introduced.

The last topic is scanning probe techniques, including scanning tunneling and scanning force microscopies. The students read a paper by Hoffman which reviews many of the scanning probe microscopies and applies them to characterization of carbon fiber materials.[3] In one problem set, students are asked to compare the types of information obtained by STM/SFM on carbon fibers with the information learned from SEM and TEM, and to explain the advantages and disadvantages of each technique.

The last group of techniques we discuss includes mass spectrometry and infrared, Raman, and nuclear magnetic resonance spectroscopies, and focuses on chemical characterization. At this point in the course, students have become familiar with the pattern of the presentation and can apply many of the concepts they learned earlier to this last set of tools. Thus, introducing each technique requires less time and we are able to shift the lecture content to more complex problems requiring multi-technique approaches. FTIR and solid-state NMR exercises examine different polymer systems and demonstrate the powerful analytical capabilities of these two instruments.

With one week of classes left in the semester at this point, we introduce a case study that involves trouble-shooting a process restart. The problem statement, (developed for us from plant experience by Dr. George Swan, Exxon Research and Development, Baton Rouge, Louisiana) includes a description of the reforming process and the catalyst changeover procedure, along with a flow sheet. Gas chromatographic analysis of the product stream and discussion of some of the attempts to find the cause of the low octane rating are also presented and are read by the students before the class discussion. In class, the students seek the solution by suggesting causes and analyzing consequences. When they suggest that new data be gathered, the wisdom of such a move is analyzed for its utility, cost, and time required. The instructor's role is to keep the students on track with a minimum of direction and to supply additional data if it is asked for and available. The twist in this problem is that the chromatography data are incomplete. Mass spectrometry is needed to discover a heat-exchanger leak that allows some of the feed to bypass the reactor. Even though this problem is relatively simple from an instrumentation point of view, the thought processes stimulated by the discussion are valuable for the students. We hope to develop additional case studies using real plant situations as the course evolves.

COURSE REQUIREMENTS

The course work includes three exams, a term paper, and ten problem sets. Exams focus on applying the principles learned. For example, one question on the first exam asks students to formulate a series of experiments to differentiate between three proposed reaction mechanisms, given a laboratory equipped with an XPS, ISS, SIMS, and a full range of isotopes. Other types of questions ask students to interpret spectra or to draw and label a schematic of an instrument.

The objective of the term paper is to get students to go into more depth for a particular technique. We give students the option to discuss a specific molecular measurement application of a technique introduced in class, or to discuss a new technique. They must submit paragraphs (which include three references from the literature) presenting their topics a month before the paper due-date so we can make suggestions and be assured they have started the assignment. Students normally choose topics that are too broad in scope and they need help focusing their ideas. A sampling of term-paper topics is given in Table 2.

Finally, we use problem sets to follow students' progress and to demonstrate application of techniques to engineering problems. We find that students respond most favorably to recent articles because they recognize the importance of these techniques in solving existing problems. In one problem set we ask students to read a recent paper, "High-Temperature in Situ Magic Angle Spinning NMR Studies of Chemical Reactions on Catalysts."[4] Although we do not expect the students to grasp all the details of solid-state NMR, we find they can understand how the

TABLE 2
Sample Term Paper Projects

- Positron emission tomography
- Scanning thermal microscopy
- Using TEM to determine inhomogeneity of highly cross-linked polymers
- Solid state NMR investigation of polymer morphology by multiple pulse spin diffusion experiments
- Chain branching studies of polymers using ^{13}C NMR
- X-ray diffraction for measuring residual stress in materials

technique is applied and what is learned, and they can also answer questions about sample preparation and suggest additional measurements which support the authors' overall conclusions.

We find it helpful, after handing back graded problem sets, to review questions which the students find difficult. These discussions, in addition to explaining the specific problem, generate additional questions. Oftentimes a student can be guided to answer his or her own question, and in many cases, help also comes from fellow classmates. Although these lectures break from the traditional lecture format, they are valuable for both the students and the instructor because they foster a more relaxed environment for learning, encourage questions, and give a measure of the students' understanding of the material.

RESOURCE MATERIALS

Because of the number of tools we cover and the broad nature of the material, we do not use one specific textbook. Instead, we use a compilation of review articles, book chapters, and papers in the literature. A chapter, "Catalytic Surfaces and Catalyst Characterization Methods," in *Chemical Industries Series*[5] serves to introduce many of the topics we cover. Since it focuses on catalytic systems, we use lectures and problem sets to challenge students to apply the techniques to other fields, including composites, polymers, and semiconductors. Papers in the literature are an excellent resource because they can be chosen to demonstrate a particular principle and to tailor the course to the interests of the students. The list of papers used (see Table 3) shows a balance of classics and the newest applications.

TABLE 3
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Finally, we recommend the students dust off their physical chemistry books when we review the background material at the beginning of the semester.

ON TEACHING TEACHERS

We would be remiss in closing this presentation without commenting on the special circumstances that brought Randy Smiley into this educational partnership. Essentially all chemical engineering lectures are given by faculty at Purdue, but we were encouraged to try this experiment through a Du Pont Fellowship granted to Randy. The success of the experiment is probably best illustrated by his own words:

> *I feel fortunate to have had the opportunity to teach a course during my graduate studies at Purdue. I was amazed at how markedly my lecture preparation and teaching style changed as the semester progressed. I became more efficient in preparing for lectures and much more relaxed in front of the students, which gave me confidence and made the students more responsive in class. The classes in which we discussed journal articles were clearly the most unpredictable and the most fun to teach. I also enjoyed developing the laboratory exercises used in the course. The period we spent at the Electron Microscopy Center gave students a view of the complexities of the equipment and sample preparation which would have been impossible to achieve in a classroom.*
>
> *Professor Delgass came to class during the first few weeks of the semester and gave me immediate feedback on my teaching style. In addition, we typically met once a week to discuss the class progress. Initially, this time was spent discussing course content, but later in the semester we talked about the other responsibilities facing a professor, including starting up a research group and writing proposals. In addition to my discussions with Professor Delgass, I found the book* Teaching Engineering[6] *helpful. It has hints about teaching skills, and discussions about tests, homework, and grading that are insightful. Overall, teaching in this supportive environment was a rewarding experience which I strongly recommend to any student who has any desire to pursue a career in academia.*

SUMMARY AND CONCLUSIONS

Understanding what tools are available and the type of information each technique gives is critical for engineers to be successful problem solvers. This course gives students the foundation of many characterization tools that will be available to them and should help bring a molecular point of view to their problem-solving skills. Exam questions and problem sets are designed to expose students to the practical potential of these tools and to hone their ability to critically evaluate the technical literature. Laboratory exercises familiarize students with instrumentation and sample requirements and demonstrate the principles taught during the lectures. Finally, case studies show students how techniques are applied directly to problems facing practicing engineers.

ACKNOWLEDGMENTS

We would like to thank the Du Pont Foundation for awarding Randy Smiley a 1992-93 Teaching Fellowship. Many thanks also to Dr. D. Sherman and Professor C.E. Bracker at the Electron Microscopy Center in the School of Agriculture at Purdue, and to Dr. Brett Cowans and Robert Adams for their help with the microscopy NMR and FTIR laboratory demonstrations.

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REVIEW: Elements of CRE

Continued from page 161.

- *Basic definitions (and the necessary un-definition that rate must not be defined as dC/dt, despite what students have usually learned in physical chemistry courses)*
- *Power-law and Langmuir-Hinshelwood-Hougan-Watson kinetics*
- *Design of ideal reactors, both isothermal and nonisothermal*
- *Using data to obtain rate expressions*
- *Product selectivity*
- *Mass transport in reaction engineering, including porous solids, slurry reactors, and mixing in nonideal flows*

Parallel to the technical exposition are difficulty-ranked problem sets and "Thoughts on Problem Solving" that are several-page end-segments of twelve chapters which discuss such formal approaches to problems as Kepner-Tregoe situation analysis.

The most striking additions woven into this edition are 1) treatments of chemical vapor deposition, biotechnology, and polymerization, and 2) emphasis on using packages for solving differential equations.

The first addition serves the obvious purpose of introducing these areas into the core curriculum, but even more subtly it also teaches how these "emerging technologies" are treatable by the classical techniques of reaction engineering. For example, I find the best way to introduce development of catalytic rate expression for heterogeneous catalysis is to

begin with Michaelis-Menten enzyme kinetics, which is done well here. Unlike inorganic catalysis, the "site" is a tangible, specific, and unambiguous location for many enzymes, thanks to experiments and molecular modeling (*e.g., Science,* **253**, 872, 1991). Fogler also treats multiphase reactors more effectively by treating both classical slurry reactors and aerobic bioreactors where air is bubbled through aqueous "slurries" of cell mass.

Student use of O.D.E.-solvers in this course is promoted through the book's examples and problems. POLYMATH (CACHE Corporation) is used in most cases, but other packages are also used or cited (*Chem. Eng. Ed.,* **24**, 54, 1991). Simple codes for some computer solutions are still provided, but the equation solvers allow a quicker transition for the students to explore solutions and effects of parameters. Fogler's approach forces emphasis on concepts over techniques, in the spirit that to use an equation solver effectively, you only need to know how it works—not how to make one. In this text, reaction engineering is the focus, while analytical or numerical methods are important tools to be used.

A strong point of the examples and problems is that real reactants and reactions are generally used. The types of chemistries involved are not structured beyond homogeneous versus heterogeneous, but it isn't (and shouldn't be) the purpose of this book to organize the suite of chemical engineering chemistry. Many students enter chemical engineering because they like chemistry, and the reaction engineering course is often the one place in the chemical engineering sequence where they seem to realize the connection with their chemistry courses. (Paradoxically, the curriculum is full of non-reaction chemistry, too, from chemical thermodynamics to materials to molecular bases of transport properties. We need to do a better job of pointing out the balance of physics and chemistry that go into the chemical engineering profession.)

Some worthwhile material has been omitted to meet space restrictions, but not always seamlessly. For example, analysis of trickle-bed reactors was eliminated, apparently to allow inclusion of bioreactors as multiphase reactors (certainly a defensible choice) but, unfortunately, trickle-bed problems are left unchanged from the first edition, as if the relevant text material was still in place. Other sources may be easily consulted, though, because references for trickle-bed analysis and design are retained in the "Supplementary Reading" section. Other topics which are mentioned only briefly include fluidized-bed and transport reactors.

Of course, not every topic can or should be included in an undergraduate course on reaction engineering. Fogler describes an excellent, semester-long sequence using about 60% of the book. Its coverage and timeliness make it today's *de facto* standard text for undergraduate kinetics and reaction engineering. ❐

ChE book review

HAZOP and HAZAN: Identifying and Assessing Process Industry Hazards, 3rd Edition

by Trevor Kletz

Published by the Institution of Chemical Engineers, United Kingdom; distributed in the US and Canada by Hemisphere Publishing Corporation, Bristol, PA; 150 pages, $49.50 (1992)

Reviewed by
Daniel A. Crowl
Michigan Technological University

This book is a significant improvement over the last release, a soft-bound edition published in 1986. This issue includes a hard cover (in standard book size), redrawn and updated figures, new references, and new content. It is divided into seven chapters, with several chapter appendices and supplemental material.

Chapter 1 provides a brief introduction to hazard identification and assessment, including a discussion of why it is important, how far one must be prepared to go to eliminate hazards, and when in the design of a chemical plant these methods should be applied.

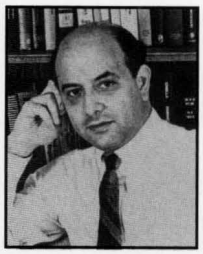
Chapter 2 presents the concept of hazard and operability studies (HAZOP), a hazard identification procedure which has become increasingly important to the chemical industry. A detailed example using the feed section to an olefin dimerization plant is provided. The chapter also includes discussion on why HAZOPs are important, who carries out the HAZOP, and the limitations to HAZOPs. An interesting appendix to the chapter describes nine accidents which could have been prevented by a proper HAZOP and one accident which most likely could not have been prevented.

Chapter 3 introduces hazard analysis, which Professor Kletz (and perhaps the British) is determined to call HAZAN, for hazard analysis. As Kletz points out, the United States prefers the term "quantita-

Continued on page 193.

THE CHANGING ROLE OF ACADEMIA

JULIO M. OTTINO
Northwestern University
Evanston, IL 60208-3120



***Julio M. Ottino** is Walter P. Murphy Professor and Chairman, ChE Department, Northwestern University. He received his PhD degree from the University of Minnesota and his undergraduate degree from the University of La Plata, Argentina. His research interests are in mixing and chaos, pattern formation—aggregation, breakup, and dispersion—and mixing of immiscible and complex fluids. He is the author of* The Kinematics of Mixing: Stretching, Chaos, and Transport *(Cambridge University Press, 1989).*

Academia is in turmoil. Higher education in the United States has never been static, but it is now undergoing rapid transformations, seemingly with no overall plan, seeking a purpose, pulled in many directions by forces that did not even exist a decade ago. Academia is now accountable to media pressure, to alumni, and to government. There are concerns about teaching, tuition costs and allocation of funding, weights given to graduate and undergraduate education and research, scientific misconduct, and in general about the perceived mismatch between academia's wants and society's needs. Critical reports have appeared in major newspapers and on television: a *Chicago Tribune* article on teaching at the University of Illinois at Urbana; a *20/20* report on teaching at Berkeley. A decade ago it would have been unthinkable to conceive of a book like *ProfScam.*[1]

The pressures are irreversible and will not go away. U.S. industry has been forced to deal with both globalization and environmental concerns, and environmental issues will not be reset as they were in the 1950s. Similarly, what is now expected of academia is quite different from what was expected in the 1960s and 1970s. Only the institutions that are able to adapt will survive.

There is a wide gap between myth and the reality of academic life. For this, academics have no one to blame but themselves, since any attempt to communicate ideas to the general public is usually looked upon with suspicion. The result is public ignorance as to how leading science evolves, the prevailing wisdom being that science somehow moves in rectilinear fashion to immutable truths.

Contrary to popular belief, there is now renewed attention being paid to undergraduate education in many institutions. My own institution, McCormick, is a good example: there are financial incentives for good teaching, such as rotating endowed chairs; 80% of the full professors teach at least one undergraduate course a year; and it is impossible to buy time from teaching. The public at large, however, has little idea of how professors spend their time.

Inside and outside forces are taking their toll, particularly on young academics who are expected to be all things to all people—great researchers, effective fundraisers, inspirational teachers. Recent statistics are not encouraging: 53% of academics under forty year of age report that "my job is a source of considerable personal strain."[2]

Many institutions are trying to redefine their missions. An ever-increasing stream of speeches and reports (many originating from captains of industry) are telling academics what to do, how to teach, how to manage their institutions, how to view research, and how to re-examine the rationale for the support of research. Some of this advice is well intended, but naive—and copying models of industrial success and applying things like TQM will help only up to a certain point. In the same way that industry cannot conduct research as if it were a university, university research cannot be managed in an industrial mode. There is just so much that can be left to serendipity[3] but tight organization will undoubtedly kill creativity.

Changes do not come without pain. Nevertheless, it is indisputable that in order for academia to remain productive, changes must be made and a new vision of scholarship must be advanced. To echo the

words of Thomas Kuhn, a paradigm shift is in the air. As to what the new paradigm will be—that is hard to predict. What rationale will colleges and universities use to redefine their mission? Will things evolve to a unique model of success? Will expectations regarding faculty performance be uniform across institutions? *Scholarship Reconsidered*[2] offers one of the best reasoned views of how this paradigm might look and what considerations should be important when judging alternatives. In the following paragraphs I will quote freely from this work, adding a few interjections of my own and restricting the remarks to research universities.

Universities have been too narrow in defining the boundaries of acceptable behavior, especially when contrasted to the historical record of academia's changing mission. The main thesis of this report is that it is essential to broaden our definition of scholarship.

The current, dominant, picture is that to be a scholar is to be a researcher. This was not always so and, in fact, this view is of rather recent vintage. Explicitly, or implicitly, the mission of academia has changed throughout the years, evolving and transforming itself from teaching to service to research. The colonial college, patterned after British traditions, took a view of collegiate life that was almost monastic. Teaching was a calling. The goal of Harvard College in 1636 was to "advance Learning and perpetuate to Posterity." The student was the center of attention, and tutoring was the preferred mode of teaching. This stage lasted for almost two hundred years, until service was added to the role.

This transformation did not happen overnight. Institutions gradually took an increased interest in serving business and economic posterity. Rensselaer Polytechnic Institute was founded in 1824 with the premise that "the United States needs railroad-builders, bridge-builders, builders of all kinds." The practical side of higher learning appeared loud and clear in the Land Grant College Act of 1862 and the Hatch Act of 1887. By 1903, the presidents of Stanford and Harvard would declare that the entire university movement "is toward reality and practicality," and that "at the bottom, most of the American institutions of higher education are filled with the modern democratic spirit of serviceableness." The first president of Cornell saw graduates "pouring into the legislatures, staffing newspapers, and penetrating the municipal and county boards of America." Academia saw itself as a major force in shaping society. There was a conviction that higher education had a moral mission to fulfill.

Where was research throughout this period? Certainly not within university walls. In fact, it took quite some time before research found a hospitable home within academia. The first advanced degree obtained by an American goes back to early 19th-century Germany, and it took another fifty years for the first PhD degree to be awarded in the United States (Yale, 1861—followed by Pennsylvania, Harvard, Columbia, and Princeton). Things moved quickly after that, however. The University of Chicago, founded in 1891, made the PhD degree the pinnacle of its academic program. In fact, within four years of its founding, its president declared that "promotions in rank and salary would depend chiefly upon research productivity."

Then, two World Wars and the Depression set the stage for a dramatic all-inclusive change, particularly in the way that research was to be supported by government.

The most quoted document involving interaction between government and academia, *Science: The Endless Frontier*—a report written for President Roosevelt at the end of World War II by Vannevar Busch of MIT, and eventually delivered to President Truman— provided a blueprint that guided research right up to the present day. Its implicit idea was one of "societal return": that the societal return obtained by government investment would be greater than that produced by the same private investment.[4] Agencies such as the National Science Foundation were created, and money started to pour into the halls of academia. By some measures this has served us well. Since 1945 United States scientists have received 56% of the Nobel Prizes in Physics, 60% in Medicine, and 42% in Chemistry.

The societal return concept does not work well in a world-integrated economy; in fact the very idea of only one country having the monopoly in education is questionable and universities would do well to think in broader terms. Nevertheless a firmly ingrained consequence of operating under this paradigm for the last half century is that academic success (indeed, scholarship) has been associated with research, and research, in turn, exclusively with discovery. This might have been a narrow viewpoint, but its appeal was unparalleled. All universities tried to fit into the mode and faculty were judged primarily as researchers; after all, there was money to be garnered from successful academic enterprises.

Scholarship goes beyond research, however. By and large, only one type of scholarship is routinely acknowledged—the Scholarship of Discovery. Based

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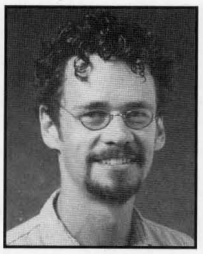
APPLIED STOCHASTICS FOR ENGINEERING

JAY D. SCHIEBER
University of Houston
Houston, TX 77204-4792



Jay D. Schieber *is Assistant Professor of ChE at the University of Houston, where he has been since 1991. He received his BS from the University of Illinois, Urbana, and his PhD from the University of Wisconsin in 1982 and 1989, respectively. He spent a year at the University of Freiburg (Germany) and another at McGill University (Canada) as a postdoctoral fellow. He has an active research program in kinetic theory, transport phenomena, fluid mechanics, and polymer rheology.*

There is an old joke that says that a statistician is someone who drowns while trying to cross a river with an average depth of three feet. But that sounds to me like the definition of a *bad* statistician. On the other hand, I have run across many otherwise *good* engineers who recognize the perils of considering only an average quantity, but have avoided probabilistic models altogether. I believe that engineers might serve themselves better in the long run by becoming good statisticians and good stochastic modelers.

There is a perceptible increase in the interest of stochastics in the chemical engineering community, evidenced by two observations: the fall 1993 AIChE meeting is slated to contain a session on "Probabilistic Models," and no less than three articles from the 1989 issues of this journal included some discussion of stochastic models in a new course description. Clearly, stochastics is playing an increasing role in chemical engineering.

Last spring our department initiated a course in introductory stochastics designed to introduce graduate students to this rapidly expanding field. Fourteen students enrolled in the course, two students audited it, and two faculty also attended regularly. The sophistication of the semester projects that were turned in suggests that the students learned a lot, and the course appeared to generate a great deal of enthusiasm.

In this article we will consider the following questions in order:

- *What is Stochastics?*
- *Why is it of interest to chemical engineers?*
- *What tools can be taught in a single semester course?*

WHAT IS STOCHASTICS?

One day in 1910, Albert Einstein had just finished working on a stochastic problem involving Brownian motion when his young son Hans Albert asked him for a *Rechenaufgabe.*[1] He thought up the following probability problem: "How long will it take til the ground is wet if it rains at the rate of 10mm/hr?" The problem is probabilistic, because rain does not fall uniformly, but rather in drops which cover (roughly) circular regions on the ground when they hit. After some portion of the ground is wet, the next drop may land completely on a dry area, completely on a wet area, or partly on each. There is no way to know where a given drop will land, so it must be treated *statistically.* Therefore, how long it takes a given portion of land to be completely wetted is not a deterministic question but a statistical one. We can find only the probability that it will take any given time to wet the ground.

Or, consider a second problem. Suppose that I take my red 1966 Volkswagen Beetle to a particular point in the salt flats in Arizona, fill it with one quart of gas, push-start it (as usual), point it north, put it in first gear, set a brick on the gas pedal, and let it go without a driver. Where will the Beetle be when it runs out of gas? If there were no wind we might be able to predict all of the forces on the Beetle and, in principle, calculate where the car will end up. But, in reality there is wind, the strength and direction of which we cannot predict. If we run the experiment many times, the Beetle will end up in a different place each time. We quickly understand that the car is subject to both random *and* deterministic forces, and the final position of the Beetle depends upon both.

"Solving" the above two problems means that we seek the probable distribution of possible outcomes.

The corresponding equations are called "stochastic" equations.* We can then roughly define stochastic equations as equations that describe a quantity (the position of the Beetle) whose evolution (in time) is determined by both deterministic (the motor, the grade, etc.) and random (wind) influences.

WHY SHOULD CHEMICAL ENGINEERS LEARN STOCHASTICS?

The engineer can quickly think up other, more relevant examples of when outside random influences can have a result on a final answer than the two given above: outside random influence on laboratory experiment measurements or plant processes; randomly fluctuating temperatures or pressures; random changes in feed stream compositions. But there are many other examples which are less than obvious. For example, concentration is the *average* number of molecules per volume in a region of space, and each molecule is acted upon randomly by other molecules. The actual number of molecules in a region of space is stochastic. The pore structure in a catalyst, or in an oil reservoir, is random. The transport of substances through these structures depends upon the random pore network. Cells *in vitro* undergo Brownian motion as they are bombarded by surrounding fluid molecules. Populations of cells may be described by stochastic birth-death equations. Polymer chains may take random conformations and be bombarded by Brownian forces.

We can make a general observation here. When working with a large, complex system (and chemical engineers are certainly interested in large, complex systems) in which it is effectively impossible to include all degrees of freedom in the system, the number of variables being considered must be curtailed. Nonetheless, in any real system, the other degrees of freedom not accounted for explicitly still have an influence, and if this influence is not considered deterministically, it must be considered statistically. At that point, the mathematical equations corresponding to the physical process are stochastic.

We can safely say that chemical engineers need to learn stochastics in order to tackle many of the new problems entering the field. Why? Because chemical engineering is moving toward smaller and smaller length scales as processes become more efficient and less consumptive of material resources. Bugs performing bioremediation are being jostled by water molecules; electrons in plasmas are colliding and reacting with large neutral species; molecules in low-pressure reactors are bouncing off of walls, diffusing on surfaces, and jumping between activation sites. At these length scales, the influence of individual molecules becomes important. But there are still too many molecules to handle explicitly for any timescale of interest, and Brownian forces will be important. On the other hand, many degrees of freedom acting on wildly different length scales appear to be ideally suited for stochastic models.

Understanding stochastics allows us to write down well-posed mathematical equations corresponding to intuitive probabilistic pictures. Equally important, that understanding helps us to design simple computer codes to solve the resulting complex partial differential equations numerically.

COURSE STRUCTURE

The course structure is outlined in Table 1. No textbooks are required for the course, but two are highly recommended. The first, by C.W. Gardner, is called *Handbook of Stochastic Methods for Physics, Chemistry and the Natural Sciences.*[2] It is an excellent handbook for mathematical solutions, is well organized conceptually, and has a good mix of theorem and description. But its background in probability is too thin for most engineers, the connection to physical problems is often minimal, and it contains no problems.

TABLE 1
Outline of Material in the Applied Stochastics Course
(Although not explicitly shown, examples are scattered throughout the course.)

1. Background ideas and definitions
- Averages, variance, moments
- Probability density function, cumulative probability
- Conditional probabilities, Bayes' Rule, joint probabilities
- Contraction or marginal probabilities
- Characteristic functions, moment generating functions
- Sample distribution functions: Gaussian, Poisson

2. Probability transformations
- General formula
- Generating random numbers
- Deterministic processes with random initial conditions
- Central limit theorem

3. Markovian concept
- Definition
- Chapman-Kolmogorov equation

4. Equations characterizing Markovian stochastic processes
- Differential Chapman-Kolmogorov equation
- Liouville equations
- Master equations
- Fokker-Planck equations
- Stochastic differential equations

5. Examples of Markovian processes
- Problems with analytic solutions
- Brownian dynamics simulations
- Dynamic Monte Carlo simulations

** We are using a broader definition of the term "stochastics" than that used by some mathematicians.*

On the other hand, the second recommended text, by N.G. van Kampen, *Stochastic Processes in Physics and Chemistry,*[3] is organized more like a physics book and contains many problems. In general, we followed more closely the overall organization of Gardiner, but used van Kampen for all developments involving master equations. Unfortunately, neither text contains information of numerical methods; a few texts do exist with some discussion of numerical techniques.[4,5]

Typically, most engineers have no formal background in probability or statistics, so a significant amount of time must be spent in the beginning with the basic definitions and concepts shown under the first heading in Table 1. For example, while most engineers know what an average and a variance are, less familiar are probability density and autocorrelation functions, or a conditional probability. We begin by playing with typically simple probabilistic (gambling) problems, incorporating these ideas so that the student gets a good feel for what information the quantities contain. This section of the course takes about three weeks. Some of the important definitions introduced here are shown in Table 2.

This is a also good time to introduce an essential concept used to great extent throughout the course: the dual descriptive character of stochastic processes. We can characterize a Markovian stochastic process either through the (deterministic) time evolution of the probability density function or through the statistical properties of an equation describing the evolution of a single trajectory. These two viewpoints are roughly analogous to Hamilton's versus Liouville's description of classical mechanics.

When we reach the second section, *probability transformations,* we are ready to begin solving physical problems. This section deals with the general problem of transforming some random variable, X, to some new random variable, Y := f(X), when the statistics of X are known and we wish to know the statistics of Y. A physical example is the orientation of network strands in a deformed rubber. Before deformation, the strands have random orientations whose distribution is isotropic, but when the rubber is deformed affinely, each strand moves deterministically to a new orientation. We are interested in finding the new orientation distribution of strands after the deformation.

Probability transformation also plays a role in generating random numbers with given distributions from random numbers drawn from a uniform distribution. The mathematician John von Neumann has been quoted as saying, "Anyone who considers arithmetical methods of producing random digits is in a state of sin." We largely avoid these problems, however, and assume that we have a suitable pseudo-random number generator available. Knuth[6] discusses statistical tests of pseudo-random number generators, and Press, *et al.,*[7] provide some concrete examples. A recent article by Hayes[8] (who cites the above quote) discusses more recent ideas and obstacles of such generators. The ideas contained therein are discussed briefly in class.

This is a good time to introduce the central limit theorem for three reasons: it contains all of the probability concepts introduced before; it plays an important role in many physical systems; and a concrete example, namely random walks on a one-dimensional lattice, provides a good segue into the next topic.

All of the concepts introduced so far are for general stochastic processes. However, the vast bulk of the mathematical literature, most physical models, and nearly all of the numerical work utilizes Markovian processes. Thus, we introduce the mathematical definition and physical interpretation of a Markov process. Intuitively speaking, these are processes where we need to know *only* the current state of the system in order to know future probabilities; knowing all of the past states of the system gives us no additional

TABLE 2

NOTE: The symbol Prob{...} reads as "the probability that" and := means "is defined as." The integrals must be taken over all possible values of the integration variables. <...> represents taking an ensemble average.

- **Probability density function**

$P(x;t)dx$:= Prob{The random variable X takes values between x and x+dx at time t} (1)

- **Joint probability function**

$P(x,t;y,t')dxdy$:= Prob{The random variable X takes values between x and x+dx at time t and values between y and y+dy at time t'.} (2)

- **Conditional probability function**

$P(x;t|y;t')dx$:= Prob{The random variable X takes values between x and x+dx at time t *given that* it had value y at time t'.} (3)

- **Averages may be found from these by**

$$\langle f(X)\rangle_t = \int xP(x,t)dx \quad (4)$$

- **Autocorrelation functions are found by**

$$\left\langle X(t)X\left(t'\right)\right\rangle = \iint xyP\left(x,t;y,t'\right)dxdy \quad (5)$$

insight into future probabilities if we know the current state.

Using the definition of Markov and Bayes' rule, we can derive the Chapman-Kolmogorov equation, a nonlinear, integral equation for the conditional probabilities of Markovian processes. This form of the equation has only limited practical use, so we can derive from that the so-called differential Chapman-Kolmogorov equation which has greater utility for our purposes: namely, the solution and description of stochastic processes. Most of the equations for the rest of the course are specific cases of the differential Chapman-Kolmogorov equation.

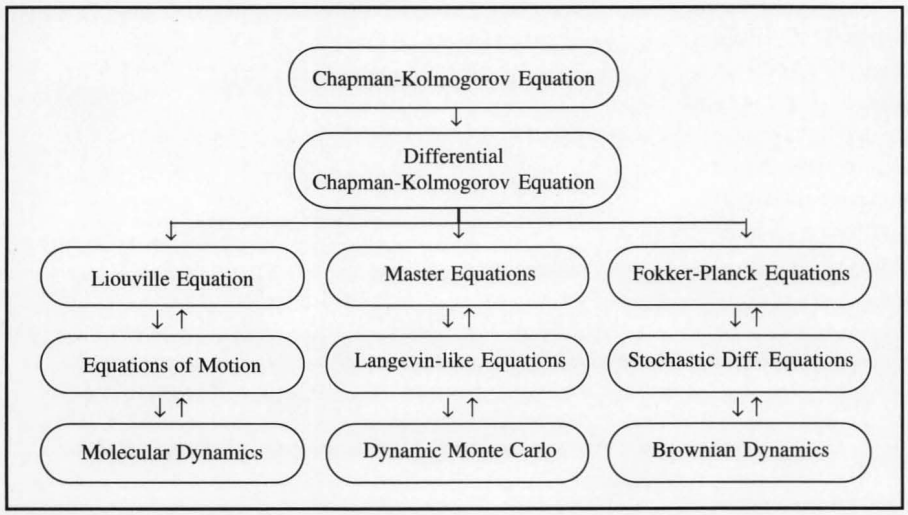


Figure 1. *Interrelation between important equations for Markovian processes.*

The differential Chapman-Kolmogorov equation can also be split into three rough catagories: 1) master equations for discrete or discontinuous jump processes; 2) Fokker-Planck equations for continuous (but nondifferentiable) diffusion processes; and 3) the Liouville equation for deterministic processes which may or may not have random initial conditions. The general forms for these equations are shown in Table 3, and the interconnection between them are shown in Figure 1.

Before deriving the differential Chapman-Kolmogorov equation from the Chapman-Kolmogorov equation, we go through derivations of simple examples of each type of equation. In addition, we repeat Langevin's derivation[9] of the first stochastic differential equation.

An entire week is spent deriving the differential Chapman-Kolmogorov equation and analyzing its different subclasses as combinations of deterministic motion, diffusive motion, and jump processes. Emphasis is placed on interconversion between the evolution equation of the probability density function and sample trajectories of the equivalent process. In this way the students get a feel for how to translate physical pictures into, say, master equations, or how to interpret the physical process represented by, for example, a Fokker-Planck equation. Many simple examples are useful here.

Finally, in this section we cover stochastic differential equations, which are intuitively very appealing—but mathematically they are usually intimidating for students on their first exposure. The primary

TABLE 3

The vector **A** describes the deterministic forces on the random vector, and **B** (or **b**) describes the random forces. The transition probability **W**(**x**|**z**,t) describes the probability per unit time that the random vector makes a discontinuous and instantaneous jump from **z** to **x** at time t. The Wiener process, $d\mathbf{W}_t$, is a delta-correlated, Gaussian white noise.

• Chapman-Kolmogorov equation:

$$P(x_3;t_3|x_1;t_1)=\int P(x_3;t_3|x_2;t_2)P(x_2;t_2|x_1;t_1)dx_2 \tag{6}$$

• Differential Chapman-Kolmogorov equation

$$\frac{\partial}{\partial t}P(\mathbf{z};t|\mathbf{y};t') = -\sum_i \frac{\partial}{\partial z_i}\left[A_i(\mathbf{z},t)P(\mathbf{z};t|\mathbf{y};t')\right] + \frac{1}{2}\sum_{i,j}\frac{\partial^2}{\partial z_i \partial z_j}\left[B_{ij}(\mathbf{z},t)P(\mathbf{z};t|\mathbf{y};t')\right]$$
$$+\int\left[W(\mathbf{z}|\mathbf{x};t)P(\mathbf{x};t|\mathbf{y};t') - W(\mathbf{x}|\mathbf{z};t)P(\mathbf{z};t|\mathbf{y};t')\right]d\mathbf{x} \tag{7}$$

• Master equation

$$\frac{\partial}{\partial t}P(\mathbf{z};t|\mathbf{y};t') = \int\left[W(\mathbf{z}|\mathbf{x};t)P(\mathbf{x};t|\mathbf{y};t') - W(\mathbf{x}|\mathbf{z};t)P(\mathbf{z};t|\mathbf{y};t')\right]d\mathbf{x} \tag{8}$$

•Fokker-Planck equation

$$\frac{\partial}{\partial t}P(\mathbf{z};t|\mathbf{y};t) = -\sum_i \frac{\partial}{\partial z_i}\left[A_i(\mathbf{z},t)P(\mathbf{z};t|\mathbf{y};t')\right] + \frac{1}{2}\sum_{i,j}\frac{\partial^2}{\partial z_i \partial z_j}\left[B_{ij}(b\mathbf{z},t)P(\mathbf{z};t|\mathbf{y};t')\right] \tag{9}$$

•Liouville equation

$$\frac{\partial}{\partial t}P(\mathbf{z};t_3|\mathbf{y};t_2) = -\sum_i \frac{\partial}{\partial z_i}\left[A_i(\mathbf{z},t_3)P(\mathbf{z};t_3|\mathbf{y};t_2)\right] \tag{10}$$

• Langevin equation

$$d\mathbf{X}_t = \mathbf{A}(\mathbf{X},t)dt + \mathbf{b}(\mathbf{X},t)\cdot d\mathbf{W}_t \tag{11}$$

impediment for students is that this is often the first time they need non-Riemannian calculus to integrate equations. But we have borrowed an introduction strategy from Gardiner that seems to be successful in getting across the importance of attaching an interpretation to any stochastic differential equation with multiplicative noise.

By the end of the section most students have little problem working with either Itô, Stratonovich, or the more recent kinetic interpretations.[10] This section requires two weeks of coverage to make the students comfortable, but the payoff for the hard work is unquestionably great since Brownian dynamics simulations are straightforward once the interpretation questions have been tackled.

I find discussion of numerical techniques to be a natural extension to the analytical solutions found for these equations. It is also at this point in the course that the students begin to see the power of stochastics. They see that complicated master equations have straightforward interpretations and may be solved easily by dynamic Monte Carlo techniques. Likewise, a complicated Fokker-Planck equation in thirty dimensions may be solved by a straightforward Brownian dynamics simulation without resorting to finite element methods.

The numerical techniques of stochastic dynamic simulations exploit the equivalence between equations of the third and fourth rows shown in Figure 1. Just as molecular dynamics techniques solve possible trajectories of interacting particles rather than the distributions function in Liouville's equation, Brownian dynamics simulations track the trajectories of realizations to estimate the probability density function in the Fokker-Planck equation. In the course, examples of Brownian dynamics simulations are given for simple polymer and cell motility models.

Likewise, the trajectories of realizations of stochastic processes described by master equations can be described by Langevin-like equations, which suggest dynamic stochastic algorithms. We show detailed examples of nonlinear reaction models that can be solved by such dynamic Monte Carlo techniques.

We spend most of the rest of the semester going through examples of how to model chemical reactions,[11] cell migration,[12] population balances, polymer dynamics,[13] transport equations,[14] lattice gas dynamics[15] for thermodynamic predictions, etc., as stochastic equations, solve them analytically or numerically, and interpret the results. These examples pull together all of the ideas introduced in the course, provide concrete examples of their utilization, and show how powerful and simple the techniques are.

TABLE 4
Term Project Topics Chosen by Students

Critical Review of Single Technical Paper
- Modeling of mechanical degradation of dilute polymer solutions
- A stochastic model of persistent currents in mesoscopic rings

General Review of Research Area
- Application of dynamic Monte Carlo simulation method in study of surface kinetics
- Stochastic models for turbulent diffusion
- Diffusion models for characterizing the firing sequences of neurons
- Stochastic two-phase flow in porous media
- Stochastic representation of reservoir heterogeneity
- Markov models for behavior
- Stochastic modeling of air pollution

Original Research
- Stochastic dynamic simulation of cubic autocatalytic reactions to study bifurcations in chemical reactions
- Stochastic modeling of coalescence of viscous drops in liquid-liquid dispersion
- Stochastic simulation of combined molecular diffusion and chemical reaction
- Solution of the Boltzmann equation by using dynamic Monte Carlo simulation
- Brownian dynamics simulation of a Hookean dumbbell with internal viscosity in steady shearing flow

TERM PROJECTS

Many of the examples in engineering are quite new. Nonetheless, I require that the students do a term project that fits into one of three categories:

1. *A critical review of a single technical manuscript that utilizes stochastic modeling.*
2. *A general review of stochastic modeling in a chosen field critiquing several manuscripts.*
3. *Original work using stochastic modeling for a research project.*

I recommended the third category primarily for those students who may have had an original idea for a simple project while working on a project in the first category. After discussion, I made specific recommendations to a few students for original projects which they followed up on.

CONCLUSIONS

Table 4 shows a list of the projects chosen by the students in each category. Surprisingly, one-third of the class chose projects which were strictly original, whereas the projects in the first category included some original work and research suggestions.

The quality of the original work was quite good,

suggesting that problems of interest to chemical engineers are fertile ground for the use of stochastics. Also, the students doing critiques of manuscripts for projects often found that much well-respected work can be greatly improved by someone with a working knowledge of stochastics.

In summary, I can write with a high probability of certainty that any chemical engineering faculty using stochastic modeling in research will find that introducing colleagues and graduate students to these techniques can be very fruitful.

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ROLE OF ACADEMIA

Continued from page 169.

on this historical record, the *Scholarship Reconsidered* report argues, however, that there are at least three other types of scholarship: Scholarship of Teaching, Scholarship of Integration, and Scholarship of Application—and that our current thinking might be too narrow to value all of them.

Scholarship of Teaching entails not only transmitting knowledge, but also transforming it and extending it as well; Scholarship of Integration is to "give meaning to isolated facts, putting them in perspective...making connections across disciplines, placing issues in a larger context, illuminating data in a revealing way, often educating nonspecialists too." This clearly points toward interdisciplinary work and drawing unexpected connections between dissimilar areas (without which some disciplines might wane and die). An acceptance of Scholarship of Application demands that we broaden our horizons as well. The usual mode is that pure is better than applied, and that things are discovered and then applied. This need not be so: new intellectual understandings can arise out of the very act of application.

The best use of the human potential already in place calls for recognition of diversity. Faculty diversity should be celebrated, not restricted, and faculty evaluation should be flexible as well as systematic—it will be increasingly more difficult to impose uniform standards on something that by its very mission should be diverse. A professor's job description is often unchanged over an entire lifetime; institutions should explore alternatives on how to sustain productivity. Creativity contracts—an arrangement where faculty define their professional goals for a three-to-five year period, possibly shifting from one principal scholarly focus to another—might offer an alternative.

It is imperative that universities become more structurally robust. Only in this way are they going to be able to deal with the pressures imposed by an ever-broadening mission. The dual mission of disseminating and transforming old knowledge while at the same time pushing the boundaries of what is known can only be fulfilled by a combination of talents and an acceptance of peaceful and profitable coexistence of various modes of scholarship. Yet, at the same time, universities cannot be all things to all people. A broader viewpoint including different models of success seems to be called for if the institutions that have served so well in the past are to withstand the pressures of the future.

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PICLES
A Simulator for Teaching the Real World of Process Control

DOUGLAS J. COOPER
University of Connecticut
Storrs, CT 06269-3222

Process control classes often become more like abstract mathematics courses as the semester proceeds. Many instructors rightly believe that there is a need for students to experience the application of classroom theory to real processes so they may appreciate not only the nuances but also the main points of the lectures.

Having spent three years in the real world of process control with Chevron Research Company, I became frustrated when I began teaching at the university level and discovered that (outside of the lab) few tools were available to me to teach many of the lessons I considered important.

Too many important concepts are lost when the bulk of assignments begin, "Start with this transfer function and . . ." For example, students must learn the serious implications that arise because transfer functions disregard that real processes are nonlinear and have measurement noise and other nonideal behaviors. They must learn to quickly and reliably perform identification studies (real-world production people can be downright ornery if one asks to experiment with their process). If they succeed in obtaining data from the process, students must learn to use it to reasonably approximate the local process behavior with a linear model—and that only then do they have the transfer function for use with their classroom design theory.

When their analysis is complete, students must learn that their controller design, no matter how sophisticated the approach, is only an initial approximation—that it must be fine-tuned on the real process. In the real world, this fine-tuning proceeds by trial-and-error and must consider both set point tracking and disturbance rejection.

The best instruction concerning the real world (short of the school of hard knocks) is obtained through carefully constructed laboratory experiences. Although we have several nice process control experiments in our laboratory at the University of Connecticut, the reality is that each study can take several hours to perform. As such, it is not reasonable to have the students explore more than the most major issues in the lab.

To teach these important lessons, the Process Identification and Control Laboratory Experiment Simulator (PICLES) was developed. The contribution PICLES brings to an existing course is that it enables the students to quickly explore many of the lessons by following the same procedures they would have to follow if working with a real process.

Douglas J. Cooper *is Associate Professor of Chemical Engineering and has been teaching process control at the graduate and undergraduate level for the past eight years. He received his BS from the University of Massachusetts in 1977, his MS from the University of Michigan in 1978, and his PhD from the University of Colorado in 1985 after three years of industrial experience with Chevron Research Company*

WHAT IS PICLES?

Let me begin by pointing out that PICLES is *not* a control system analysis or design package. Quite the opposite, this software provides realistic processes that students can use to practice the analysis and design methods they are taught. Students say that PICLES is easy, and even fun, to use. Most commands can be executed with simple key-strokes. Colorful graphics help the students follow the action on the screen as the results of their decisions unfold.

The processes in PICLES encompass a variety of behaviors. The processes have varying degrees of nonlinearity so students can explore how process behavior can change with the operating regime. This also lets them practice compromising controller tunings to maintain stability over a wide range of nonlinear operation.

The processes range from low to high order and

Having spent three years in the real world of process control with Chevron Research Company, I became frustrated when I began teaching at the university level and discovered that (outside of the lab) few tools were available to me to teach many of the lessons I considered important.

have different process gains, time constants, and apparent dead times, so students can investigate how these phenomena affect process behavior and controller stability. The processes have noise in the sampled data so students can see that, in practice, the difference between a 10% overshoot and a 15% overshoot can sometimes be indistinguishable.

In the current release (version 2.1), available controllers are all PID, and with PICLES it is easy to explore all combinations from P-only to full PID control. Because each process has colorful, dynamic graphics, after performing a controller design students can implement their solution and obtain immediate visual feedback on system performance.

There is a PID Velocity algorithm and a PID Position algorithm, so students can observe the consequences of reset windup. They can select "Derivative on Measurement" or "Derivative on Error" so they can see what "derivative kick" is all about. Some controllers require the student to enter the bias or null value, while others have a bumpless feature where the bias is automatically set in a fashion similar to what they would encounter with some commercial controllers.

There are also model-based controllers in PICLES. A Smith predictor enables students to observe how dead time affects controller performance and that dead time compensation offers real benefits. A Feed Forward element permits them to see how disturbance rejection works using both static and dynamic compensators. Decouplers enable them to explore methods for minimizing loop interaction on the distillation column.

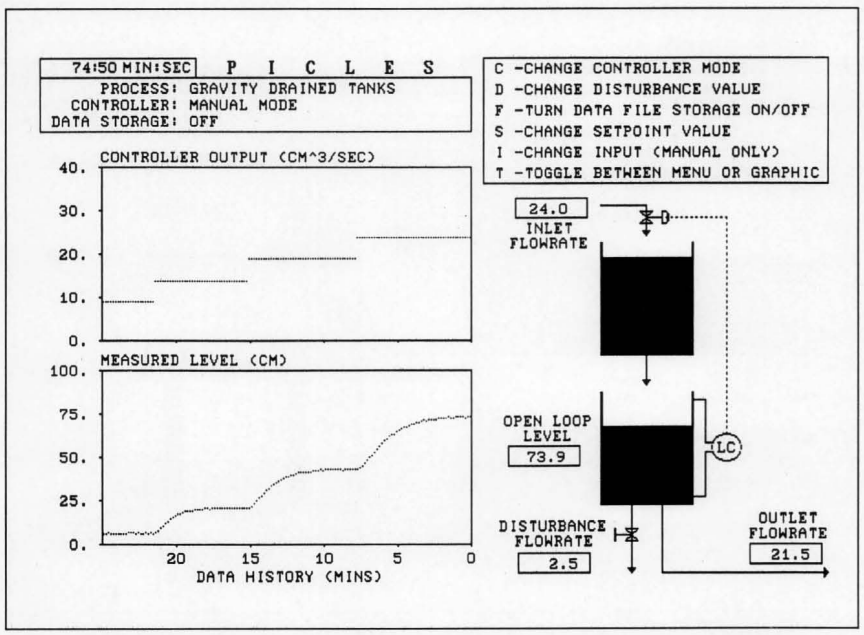

Figure 1. *Gravity Drained Tanks shows nonlinear behavior.*

COMPUTER SYSTEM REQUIREMENTS

PICLES is designed to run on IBM-compatible personal computers. The computer must have at least EGA graphics, although VGA graphics provides better resolution. For rapid execution, a computer with a '386 or '486 processor should be used. A math coprocessor is not required, but it adds additional speed to program execution.

THE PICLES PROCESSES

Gravity Drained Tanks • This process, shown in Figure 1, is two non-interacting gravity-drained tanks in series (see assignment 1b later in this article for more about the figure). The manipulated variable is the flow rate of liquid entering the first tank. The measured/controlled variable is the liquid level in the second tank. This process displays a nonlinear behavior because the drain rate from each tank is proportional to the square root of the hydrostatic head (liquid level in the tank). The disturbance, or process load, is a flow out of the second tank due to a positive displacement pump. Hence the disturbance is independent of level except that it loses suction at extremely low liquid levels in the second tank.

Heat Exchanger • This process, shown in Figure 2, is a counter-current lube oil cooler (see assignment 3e later in this article for more about this figure). The manipulated variable is the flow rate of cooling water on the shell side. The measured/controlled variable is lube oil temperature exiting the exchanger on the tube side. An interesting characteristic of this nonlinear process is that distur-

bances, generated by changing the flow rate of warm oil that mixes with the hot oil entering the exchanger, display an inverse or nonminimum phase behavior. The process also has a negative steady state gain.

Design a Process • Design a Process has a display, shown in Figure 3, that is similar to that found on commercial controllers (see assignment 6a for more about this figure). It permits students to input a transfer function and obtain a visual appreciation when studying problems found in textbooks. The student can specify a steady state process gain, an apparent dead time, up to three process time constants, and a valve time constant. It is also possible to specify a "linearity factor" if a nonlinear process is to be designed.

Mystery Processes • These processes are not really mysterious. Rather, they are simply Design a Process with a fanciful name and with all parameters pre-specified and hidden from the student. Thus each Mystery Process displays a behavior that ranges from first to fourth order and has different overall process gains, time constants, apparent dead times, and degrees of nonlinearity. Because there is no *a priori* indication of expected process behavior, the student must rely strictly on process identification studies for controller design. This simulates the disassociation that is often felt when tuning controllers from a remote control room and makes the simulations perfect for project work later in the semester. All of the mystery processes use the same graphic as shown in Figure 3.

Pumped Tank • This process is a surge tank. The manipulated variable is brine flow rate out of the bottom of the tank and is adjusted with a throttling valve at the discharge of a constant pressure pump. This approximates the behavior of a centrifugal pump operating at relatively low throughput. The measured/controlled variable is the liquid brine level. This surge tank presents an interesting control challenge because of the integrating nature of the process. The disturbance variable, or process load, is the flow rate into the tank.

Distillation Column • The Distillation Column, shown in Figure 4, is a binary distillation column that separates water and methanol (see assignment 8a for more about this figure). The column dynamics are simulated using a model published by Wood and Berry.[1] There are two controlled variables and two manipulated variables. The reflux rate controls the distillate composition and the rate of steam to the reboiler controls the bottoms composition. The feed rate to the column is the dis-

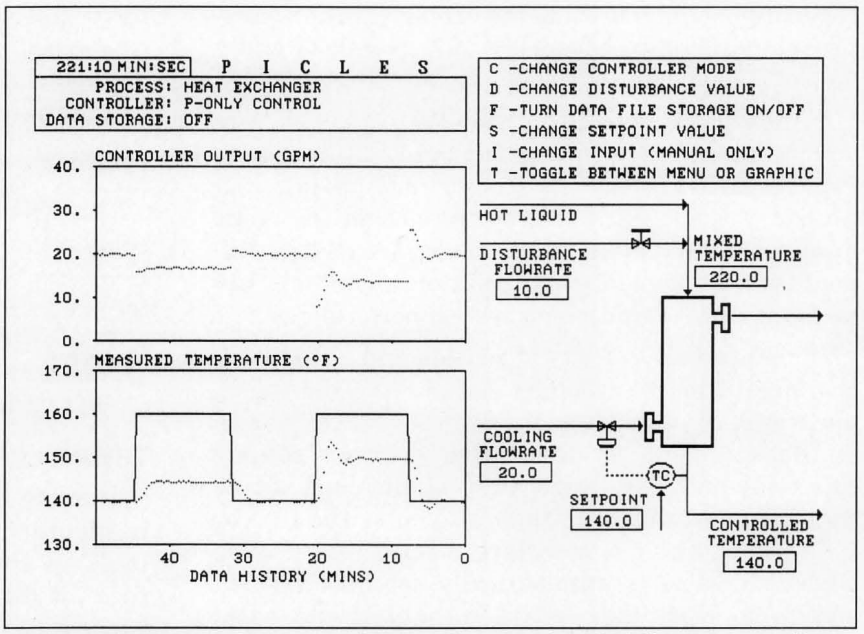

Figure 2. *Heat Exchanger under P-Only control with different controller gains.*

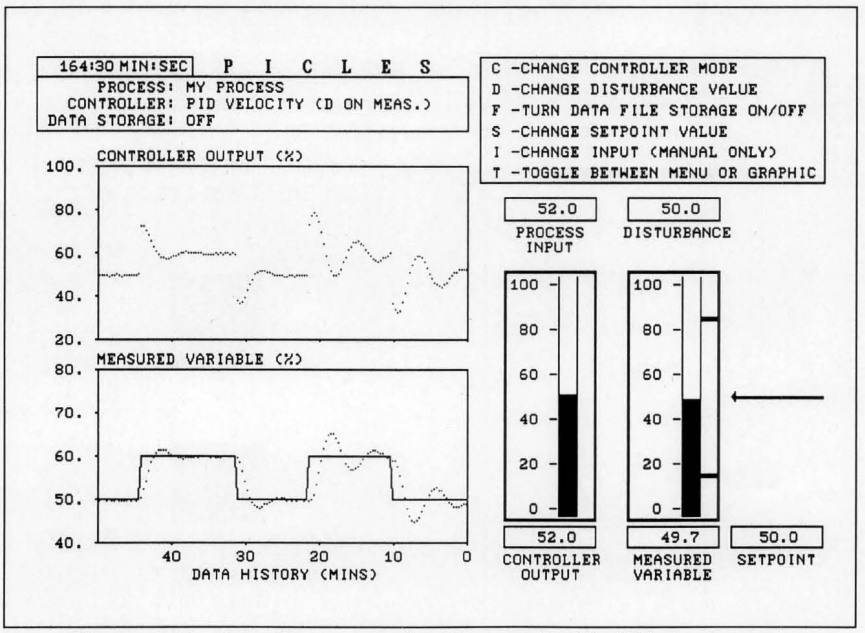

Figure 3. *Design a Process under PI control with differing amounts of dead time.*

turbance variable. This process illustrates interaction between two controllers.

AVAILABLE CONTROLLER MODES

The control algorithms in the current version of PICLES are all PID and include

- Manual Control
- P-Only Control (Manual Bias)
- Velocity PID Control (Derivative on Measurement)
- Velocity PID Control (Derivative on Error)
- Position PID Control (Bumpless)
- Velocity PID with Smith Predictor
- Velocity PID with Feed Forward
- Velocity PID with Decoupler (Distillation Column Only)

Version 3, which will be available in 1994, will include I-Only control and a discrete controller algorithm.

Figure 5 shows the Design Menu used to specify controller parameters. The process being simulated in this figure is the Heat Exchanger process (see assignment 5a for more about this figure). Note that the simulation noise level can be changed if it is appropriate for an assignment. Also, in the spirit of the "real world," high and low alarms can be set to provide additional challenge in using the program.

Although the limitation to PID algorithms is viewed as a serious limitation by some, I try to exploit this fact within the classroom lectures. For example, I establish that the PID controller is a special case of the Internal Model Control design method. Also, I show how the Smith Predictor is a limiting case of some predictive controller design methods. Thus, PICLES can be used to explore certain aspects of these newer design standards.

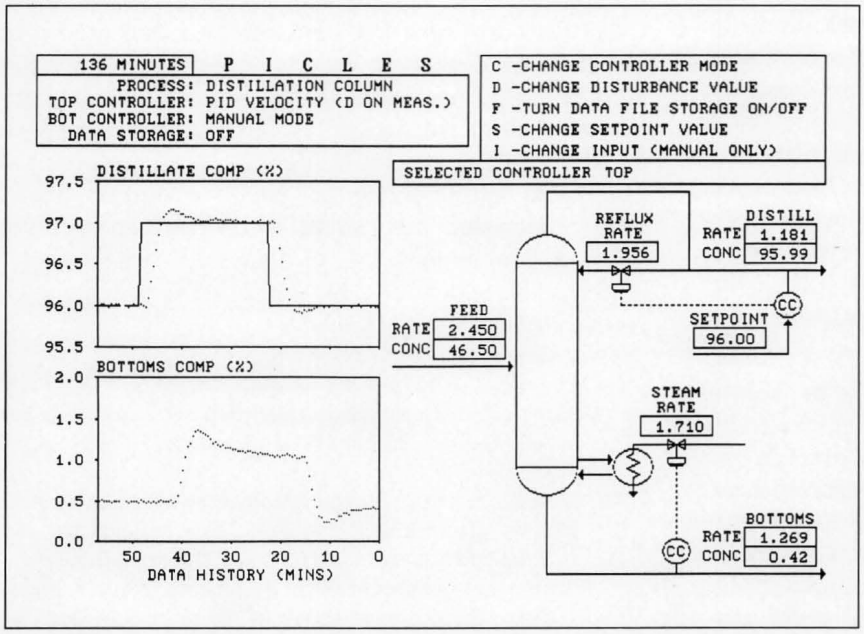

Figure 4. *Distillation Column with Distillate under PI control and Bottoms in Manual*

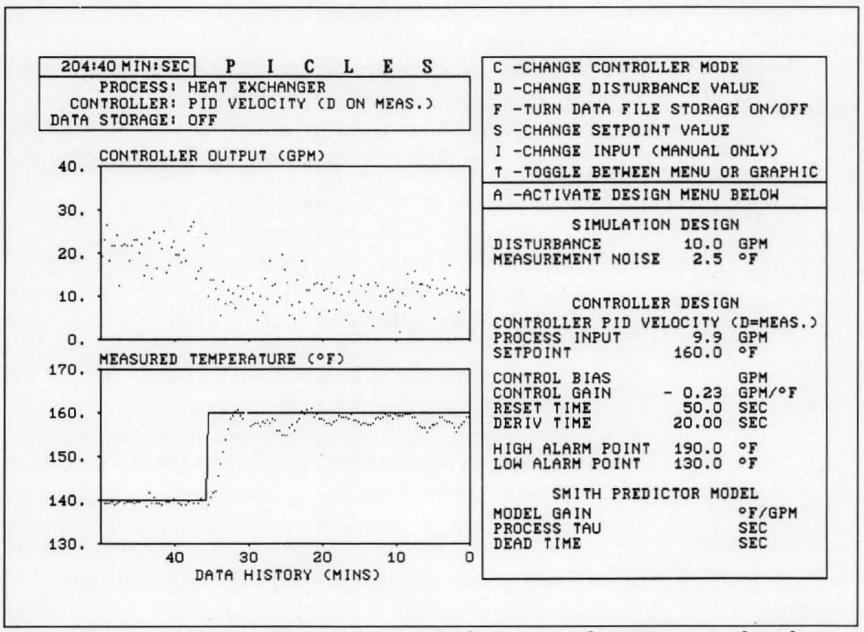

Figure 5. *Design Menu of Heat Exchanger under PID control with measurement noise.*

USING PICLES IN THE COURSE

I start with the Gravity Drained Tanks process. The model can be easily derived in class, it behaves intuitively, and the nonlinear behavior is modest. The simulation graphics also provide realism to help give the students an understanding of the dynamic behavior of the process.

Since I believe that some practice in programming is important, I also have the students code up their own Gravity Drained Tanks process based on the equations derived in class. I then have them determine the process parameters which cause their simulation to approximate the dynamics of the PICLES simulation.

After several assignments in process dynamics and process identification, I move on to the Heat Exchanger.

It is a slightly more complicated process, but it still behaves intuitively. It has a higher degree of nonlinearity and also has a negative steady state gain, which reinforces my lecture that gains not only have magnitude and units, but also a sign. The nonminimum phase or inverse dynamics of the disturbance response provides another new twist.

After they have explored several investigations of process dynamics, some identification methods, and explored a few controllers and design techniques using Gravity Drained Tanks and Heat Exchanger, I use the Mystery Processes for project work. I assign a different Mystery Process to each group of students and let them tie things together by doing an identification, preliminary controller design, and finally determining a single "best" tuning for both set point tracking and disturbance rejection, all as one assignment. Because the processes are nonlinear, each student can have his or her own project by specifying different ranges of operation for each problem (*i.e.,* Amy must design for an output range of 20-30%, etc.).

I use Design a Process intermittently to isolate specific process behaviors. For example, I ask the students to implement a true first-order process under P-Only control and let them demonstrate that such a process is unconditionally stable for all values of controller gain. They then show that a second-order process under P-Only control can approach the limit of stability, and finally, that higher order processes under P-Only control can go unstable. When combined with a class discussion on system stability using root-locus, the students benefit from relating theory to practice while the subject is being taught.

As another example of using Design a Process later in the course, I assign a set of time constants and a process gain and ask the students to design and validate a controller. Then, keeping those process variables and tuning parameters fixed, they add dead time to the process and discuss their observations on the effect dead time has on closed-loop performance. Finally, they design and implement a Smith predictor to relate our in-class derivations and discussions with actual application to assist them in understanding the benefits of dead-time compensation.

When the students start feeling confident, I give them the Pumped Tank process. The integrating nature of the process really surprises them and requires me to do a lot of explaining ("Why is there no offset with a P-Only controller?" "How come with a PI controller, this process goes unstable when the controller gain is too high *and* too low?").

Finally, the Distillation Column lets the students see what can happen when more than one controller is operating on the same process. The interactions show them that optimizing controllers individually does not necessarily produce an optimum solution when the controllers begin to interact. Also, the students can investigate how model-based decouplers can work to minimize this interaction.

EXAMPLE HOMEWORK ASSIGNMENTS

To illustrate how PICLES can be integrated into an existing course in process control, this section lists sample homework assignments. These assignments follow the order of development used in most textbooks and let students visually appreciate these important concepts. The five figures previously discussed also serve as partial answers to selected problems.

Assignment on Process Dynamics

1. Using Gravity Drained Tanks in Manual mode:
   a. Plot and discuss how the measured level responds to step changes in the manipulated inlet flow rate and the disturbance flow rate. Comment on the natural stability of the process.
   b. Starting from three different steady state operating regimes, plot how the measured level responds to manipulated inlet flow rate perturbations of fixed size. Based on these plots, discuss the nonlinear nature of the process. (*Answer:* Figure 1 shows the nonlinear nature of the process because the measured level responds differently for three step changes of equal size in the manipulated inlet flow rate.)

Assignment on Process Identification

2. Using Design a Process:
   a. Generate an open loop input/output step response curve for a true first-, second-, and third-order process. How does the time to 63.2% of change compare to the time constants assigned? Discuss your conclusions.

Assignment on P-Only Control

3. Using the Heat Exchanger in P-Only mode:
   a. For a design operating temperature, determine the value and units of the controller bias.
   b. Obtain a FOPDT (first order plus dead time) model describing process dynamics around this design temperature and use it to compute a P-Only controller gain using ITAE, direct synthesis, IMC, etc.
   c. Starting with this controller gain and bias value, use trial-and-error to find the "best" gain, where for this assignment "best" is defined as a 10% overshoot for set point steps of a specified size. Now show the ability of this "best" controller to reject step disturbances.
   d. Starting from the design operating temperature and using your "best" tuning, make set point step changes of various sizes in both directions. Discuss your observations on offset.

e. Pick a specific set point change and plot the response of the process when using your "best" controller gain, half of that gain, and twice that gain. Discuss your observations on the relationship between controller gain and offset. (*Answer:* Figure 2 shows set points steps with two different controller gains, and that offset and the oscillatory nature of the response changes as controller gain changes.)

Assignment of PI Control

4. Using Gravity Drained Tanks or Heat Exchanger in PI velocity mode:
   a. Explain why no bias is necessary for this controller.
   b. Obtain FOPDT model describing process dynamics around a design point of operation and use it to compute a PI controller gain and reset time using ITAE, direct synthesis, IMC, etc.
   c. With these parameters as a starting point, use trial-and-error to find the gain and reset which provide a "best" performance. Here, "best" performance is defined as a 10% overshoot and a 25% decay ratio to a set point step of specified size. Why can we design for two performance criteria with a PI controller, but only for one with a P-Only controller?
   d. Plot a matrix of process responses for the same set point step where this matrix includes all combinations of your "best" tuning, a gain that is double and half of your "best," and a reset time that is double and half your "best." Use your observations to explain the roles of gain and reset time on controller performance.

Assignment of PID Control

5. Using the Heat Exchanger in PID velocity mode:
   a. Design and implement a PID controller and compare its performance to PI control. For this comparison, test a number of set point and disturbance scenarios and show where the derivative action really pays off. Plot the distinctive scenarios and use them to explain why or why not any performance benefit occurred. (*Answer:* Figure 5 shows that derivative action can produce very poor performance when employed on a noisy measured variable.)

Assignment on Dead Time and the Smith Predictor

6. Using Design a Process in PID with Smith Predictor mode:
   a. For the assigned process gain and set of time constants, design and validate a PI or PID velocity mode controller that gives a 10% overshoot and a 25% decay ratio for a given set point step. Keeping the process variables and tuning parameters constant, add dead time to the process and discuss your observations on the effect dead time has on closed-loop performance for this same set point step. (*Answer:* Figure 3 shows two sets of set point steps. PI controller tuning is fixed throughout. Controller performance is markedly different for the first set point steps where the process possesses no dead time compared to the second set of steps where the process possesses thirty seconds of dead time.)
   b. Keeping the same process gain, set of time constants, and including the dead time, tune your controller to again produce a 10% overshoot and a 25% decay ratio. Compare this plot and tunings to the case where no dead time was present. Discuss your observations.
   c. Now design and implement a Smith Predictor and again tune the controller to produce a 10% overshoot and a 25% decay ratio. Compare this plot and tunings with the previous two cases and discuss the pros and cons of dead-time compensation.

Assignment on Disturbance Rejection and Feed Forward

7. Using Gravity Drained Tanks or Heat Exchanger in PID with Feed Forward mode:
   a. For the design point of operation, develop a FOPDT model of the disturbance-to-output dynamic relationship. Using this model, compare a static and a dynamic feed-forward compensator for step changes in the disturbance variable.
   b. For the Gravity Drained Tanks, the disturbance immediately impacts the measured variable while there is a lag before input variable manipulations can compensate. Explain how this influences your comparison of the static and dynamic compensators.
   c. For the Heat Exchanger, there is a reasonable lag before a disturbance impacts the measured variable. Discuss how this influences your comparison of the static and dynamic compensators.

Assignment of Multivariable Control and Decoupling

8. Consider controller design for the Distillation Column when given specified design operating concentrations for the distillate and bottoms.
   a. While the bottom controller remains in Manual mode, design and implement a PI controller for the top controller. Plot the performance of the controller for distillate concentration set point steps both up and down. (*Answer:* Figure 4 shows one possible solution to this question.)
   b. While the top controller remains in Manual mode, design and implement a PI controller for the bottoms controller. Plot the performance of the controller for bottom concentration set point steps both up and down.
   c. Using the controller tuning parameters from a and b above, implement PI controllers on both loops. Make set point changes for both controllers and discuss loop interaction.
   d. Now design and implement both static and dynamic controllers. Perform the same set point changes as in part c and discuss the impact of model-based decoupling.

FINAL NOTE

For more information about PICLES and available teaching materials, write to the author at the Chemical Engineering Department, University of Connecticut U-222, Storrs, CT 06269-3222.

ACKNOWLEDGMENTS

I would like to thank the students without whom PICLES would not exist. These include *Architects:* Allen Houtz, Robert Schlegel, and Adam Lalonde, and *Builders:* Scott Ferrigno, Ralph Hinde, Jr., Larry Megan, C. Steven Micalizzi, Phil Pearson, and Yan Wan.

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THE QUEST FOR EXCELLENCE IN TEACHING

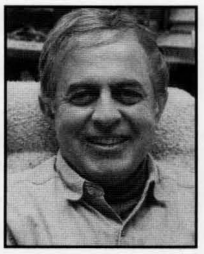
RAFFI M. TURIAN
University of Illinois at Chicago
Chicago, IL 60680

I believe that teaching is the most transcendent of all the responsibilities of a university professor, and that the search for excellence in teaching must stand as a continuing quest for each of us. There is a view, held by some, that teaching and research are antagonistic endeavors; that one can only be done well at the expense of the other. I do not share this view. I believe that, carried out in proper balance, teaching and research should be mutually reinforcing.

Nonetheless, although it is expected that being a contributor to creating knowledge is a defining attribute of teaching at the university level, there *are* good teachers who do not do research. They are not usually recognized. Yet, the obligation to teaching is so primary and broad that, in instances when research or other obligations are in conflict with it, it must take precedence.

I believe the prerequisites for excellence in teaching to be: mastery of subject; broad knowledge of the field; meticulous preparation; faith in the potential of, and the promise in, each student; the ability to invest one's subject with purpose; the sensitivity to temper rigor with forbearance and firmness with compassion; the courage to hold to one's convictions; and the humility to admit error. It is difficult to measure excellence in teaching with precision. Indeed, it is difficult to define good teaching, although one will recognize it when one sees it. Good teachers are shaped by personal experience; the perception of what constitutes excellence in teaching is uniquely personal. This constitutes my personal statement on excellence in teaching. It is a tribute to those who have taught me.

My high school was an English boarding school in Cyprus. We took English, French, classical Greek, Latin, biology, differential equations, physics, chemistry, the history of the British Empire, and cold showers at 5:00 every morning. It was rigorous and it was hard. But it was bearable, except for the English food.



Raffi M. Turian *is Professor of Chemical Engineering at the University of Illinois at Chicago. He received his BS from the University of Maryland, and his MS and PhD from the University of Wisconsin. He has held faculty positions at Syracuse and Texas Tech Universities and has also worked with Shell and the National Science Foundation. His teaching and research are in transport and fluid-particle processes.*

I remember high school as a time when I discovered that I loved poetry, literature, history, music, the sunrise, and mathematics. High school was a profoundly enriching experience; learning was a continual process of discovery. It was also a time of self-discovery. I had great teachers. They all had degrees in their subject areas and a deep interest in the subjects they taught. They did not seem to be bothered by whether or not we were having fun. They were very serious about their tasks.

We did not study American history in high school. Later, as a freshman at Maryland, my teachers were intrigued by my curiosity and interest in American history. Little did they suspect that when one has been taught to get excited about Disraeli, Palmerston, Metternich, and the politics of the balance of power in Europe, it is not difficult to get excited about Jefferson, Madison, and the politics of the power of human rights in the New World.

American history, modern poetry, and Homer stand out as the most memorable subjects from those Maryland days. It was not that chemical engineering couldn't also be exciting—but that was to come later. As a graduate student at Wisconsin I sat in the classes and in the midst of inspiring teachers: Olaf Hougen, R. Byron Bird, W. R. Marshall, Edwin Lightfoot, and Warren Stewart. Chemical engineers recognize them as men of towering scholarly reputations. I, however, stand as witness to the fact that of all their impressive achievements, the most memorable measure of their standing was the special car-

ing with which they held the humblest of students. I was in the presence of great teachers, and I felt it. I knew that I would be fortunate if I succeeded in emulating any of them as my personal example.

Through the years I have continued to learn and draw inspiration from many others: colleagues such as Chi Tien at Syracuse and Sohail Murad here, and students like Raj Rajagopalan of Houston, Alkis Payatakes of Patras, and Hemant Pendse of Maine. Perhaps I have taken something from each of my different teachers, and if so, I hope I have passed on the legacy to my own students. Great teachers are our link to greatness from the past, as our students are our link to the future. That is why the quest for excellence in teaching is a solemn obligation. Great teachers are also good students.

Good teaching is done inside as well as outside the classroom. One must have mastery of subject to enrich content, and broad knowledge of the field to place it in context and to invest it with purpose. But command of subject cannot replace preparation. Good organization, careful writing, and a pace of presentation appropriate to material and audience suggest respect for subject, seriousness of purpose, and sensitivity to student needs. The classroom presentation is not a performance, with the teacher as actor and the students as audience; they are the entire show.

Chemical engineering is a human activity. I try to infuse my classroom presentations with examples of brilliant achievements of real chemical engineers, teachers, and practitioners. I tell them that a great nation needs good chemical engineers just as it needs good poets. Otherwise, neither could its chemical engineers do a good job refining its oil, nor its poets reach for refinement in expressing its values or framing its ideals. Perhaps, ideally, a great nation needs good chemical engineers who are poets.

Good teachers are humorous when appropriate, and try to make their lectures exciting, without making entertainment or the kindling of deep emotions their highest aims. Above all, good teachers stand before students and teach them something that they know well and believe in deeply.

There was a time when I told my students that the purpose of education was not to teach them how to make money, but how to spend it well after they made it. That time is gone. Today we must teach them how to make money as well as how to spend it wisely. But I do not lament the passing of those gentler times. The challenge before us now is how to turn our students into concerned, thinking individuals with durably marketable skills, without making the catering to a current job market our highest aim.

I try to infuse my classroom presentations with examples of brilliant achievements of real chemical engineers, teachers, and practitioners. I tell them that a great nation needs good chemical engineers just as it needs good poets.

Great teachers do not yield to current fads; that is what university administrators do.

Being a good teacher means spending a lot of time with the weakest students, without losing touch with the best. It means being able to recognize and celebrate what is best in each student, without being blind to what is deficient. It means taking the time to discuss an exam with them, without conceding that the grade they have received is only a first offer. It means writing recommendation letters, even on short notice. It means helping some get scholarships, others to find jobs or to get into graduate school, and still others to get help or to seek counseling. It means meeting with parents, describing to them what we do, and if they have trust in us, as most of them still do, to demonstrate that their trust is well-placed; and if they have misgivings, as increasing numbers do, to reassure them that we are aware of their concerns and that we care.

Above all, good teaching requires that we call students to duty and that we insist they assume primary responsibility for their own learning. The hallmark of education is honesty, and honesty requires that students be told that learning is hard; often painful. That not all of us are great teachers, or even care to be. That it is possible to have fun here, but if that is *all* they want, there are better places for them—perhaps a tropical resort. That if they set their threshold for excitement high they will miss all that is full of wonder around them. That if they learn to have reverence for small wonders, they will discover exaltation in bigger ones. And that there is no entitlement to a degree in chemical engineering; only a fair chance at earning it—through hard work and honesty.

I believe that excellence in teaching is not a state of being, but rather a continual search. It is said that with prose one transmits thought, with poetry one reaches for revelation. I hope that some day before I take up poetry full time, I will have touched it in my teaching.

But then, great teaching is not in the attainment; it is in the quest. ❐

THE FREE ENERGY OF WETTING

WILLIAM G. PITT
Brigham Young University
Provo, UT 84602

William G. Pitt *is an associate professor in the Chemical Engineering Department at Brigham Young University. He is active in AIChE as the student chapter advisor at Brigham Young University and as chair of the National Student Paper Competition. He obtained his BS from Brigham Young University and his PhD from the University of Wisconsin, Madison. His research activities deal with adhesion phenomena on biomedical polymers and in polymer composites.*

The wetting and spreading of liquids on solids is frequently encountered in the chemical industry. Examples include the application of herbicides, adhesives, inks, paints and other coatings, flotation of minerals, containing and cleaning chemical spills, waterproofing, cloud seeding, lubrication, corrosion protection, enhanced oil recovery, and more. Despite its importance, however, wetting and spreading in the chemical process industries is often without a home in most undergraduate chemical engineering curricula.

The subject could be taught in classes on engineering materials, plant design, or separations. An informal survey of nine undergraduate texts[1-9] on engineering materials found that six of them mentioned the concept of surface energy, but only in the context of nucleation[1-5] and fracture propagation.[5,6] Only one of these texts introduced the concept of contact angle and presented Young's equation in a discussion of heterogeneous nucleation,[1] and none discussed wetting or spreading of liquids on other liquids or solids. Unfortunately, the only text on engineering materials that discussed contact angle, spreading, and wetting is no longer in print.[10]

This paper will present some simple but powerful thermodynamic concepts that can be taught in a 1-hour lecture on wetting and spreading. We approach the subject through the theme of the minimization of free energy—a concept with which chemical engineering students are well acquainted.

TO SPREAD OR NOT TO SPREAD

The two practical questions about spreading and wetting which an engineer usually addresses are:

- *Does the liquid spread completely or only partially on the solid surface?*
- *If partial spreading occurs, what is the contact angle of the drop on the surface?*

To address these questions we begin with the definition of the surface energy, γ, which is defined as the change in free energy as new surface area is created. If new surface is created under reversible conditions at constant pressure, temperature, and number of molecules, this surface energy is the change in Gibbs free energy[11]

$$\gamma = \left(\frac{\partial G}{\partial A}\right)_{P,T,n} \tag{1}$$

where G is Gibbs free energy and A is the surface area. If the surface is created at constant volume, temperature, and number of molecules, this surface energy is the change in Helmholtz free energy

$$\gamma = \left(\frac{\partial F}{\partial A}\right)_{V,T,n} \tag{2}$$

Because pressure is generally a more constant parameter than volume, Eq. (1) is sometimes (but not always) preferred. In this paper, the term *free energy* can refer to either of these definitions, depending on whether the wetting and spreading occurs under constant pressure or volume. Thus, the free energy associated with the surfaces of a system is simply the surface area of each phase boundary multiplied by γ for that boundary. Subscripts of γ refer to the surface free energy of the interface between the liquid, solid, and vapor phases.

Next let us perform a thought experiment suggested by Figure 1 in which we force a small drop to spread over a large surface. Before a drop of liquid contacts the surface, the surface free energy of the system is the solid-vapor surface free energy, γ_{sv}, multiplied by the solid area (assuming the original

area of the drop is much smaller than the solid area). When the liquid is spread completely on the solid, the system now consists of two interfaces (the solid-liquid and the liquid-vapor interfaces), and the surface energy of the system is $\gamma_{lv} + \gamma_{sl}$ multiplied by the solid area. One may now ask the question, "Does the system attain the lowest free energy when the drop is spread completely on the solid?" If so, complete spreading will occur. We can see that if the γ_{sv} is larger than the sum of $\gamma_{lv} + \gamma_{sl}$, the reduction in free energy will drive the drop to spread completely over the surface. Thus, spreading occurs if

$$\gamma_{sv} > \gamma_{lv} + \gamma_{sl} \quad \text{or} \quad 0 < \gamma_{sv} - (\gamma_{lv} + \gamma_{sl}) \tag{3}$$

Complete spreading will also occur if

$$\gamma_{sv} = \gamma_{lv} + \gamma_{sl}$$

because the drop will flatten out until it has a contact angle of zero (as will be shown in the next section).

In the early 1920s, Harkins and Feldman[12] studied the spreading of organic liquids on a number of solid and liquid substrates. They defined a "spreading coefficient," S, as the difference between the work of adhesion, W_a, and the work of cohesion W_c. The work of adhesion is the work per interfacial area needed to separate two adjacent (solid and liquid) phases:

$$W_a = \gamma_{lv} + \gamma_{sv} - \gamma_{sl}$$

The work of cohesion is the work per area needed to separate a single liquid phase:

$$W_c = 2\,\gamma_{sv}$$

Therefore, the spreading coefficient becomes

$$S = W_a - W_c \tag{4}$$

$$S = \gamma_{sv} - (\gamma_{lv} + \gamma_{sl}) \tag{5}$$

Harkins and Feldman observed that liquids spread completely when $S \geq 0$, which is consistent with Eqs. (3) and (5).

One final note on spreading concerns the rate or kinetics of spreading. The velocity of the moving three-phase contact line at the edge of the drop can be as high as 30 cm/s and is dependent upon the viscosity and surface energy of the spreading liquid.[11] Brochard and deGennes show that the change in the drop radius, R, with time (the velocity) is proportional to R^{-9}.[13] Thus the latter stages of spreading can be a slow process.

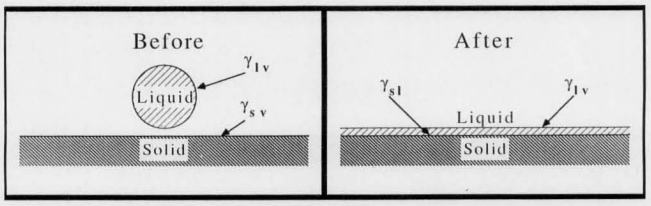


Figure 1. *Process of complete spreading of a liquid drop on a solid substrate.*

This paper presents some simple but powerful thermodynamic concepts that can be taught in a 1-hour lecture on wetting and spreading. We approach the subject through the theme of the minimization of free energy...

If the spreading occurs on a liquid instead of a solid, the velocity varies inversely with the substrate viscosity.[14] The viscosity of the surrounding fluid also plays a role, especially if the fluid is a liquid (instead of a gas). The spreading velocity increases as the viscosity of the displaced liquid decreases. More importantly, a stable liquid film separating the drop from the substrate prevents the initial formation of the three-phase contact line, and in most practical cases, the stability of this liquid film controls spreading. Thus, spreading entails multifarious phenomena, and its complexity should not be underestimated by the simplicity of the thermodynamic statement of Eq. (3).

PARTIAL SPREADING

We will now examine the case in which the solid surface energy is less than $\gamma_{lv} + \gamma_{sl}$, or in which S is negative and the spreading is not complete. In this case the drop forms a sphere or spherical cap on the solid as long as the drop is small enough that gravitational distortion of the shape is negligible. The contact angle is defined as the angle between the solid-liquid interface and the liquid-gas interface at the edge of the drop. In 1805, Thomas Young stated (without proof) that the equilibrium among the attractive forces between particles of fluid and particles of solid will cause the fluid to form a certain angle with the solid.[16] This angle was defined by

$$F_s = F_{sl} + F_l \cos\theta \tag{6}$$

where the F_s, F_{sl}, and F_l refer to the forces of the solid, the common surface, and the liquid, respectively. This was the genesis of Young's equation, a mechanical balance of rather ill-defined forces. In introductory texts, Young's equation is often taught as a force balance at the edge of the drop. While this model of a force balance is convenient and easy to teach, many students find it unsettling. They see little logic in a force balance in the horizontal direction, but not in the vertical direction. They may also

have trouble conceiving surface energy as a force per linear distance because most chemistry courses introduce γ as an energy per surface area.

Of course, both of these apparent inconsistencies can be adequately addressed.[17,18] There is a force balance in the vertical direction: just as students learn in their introductory physics course, *when you push against an immovable wall, the wall exerts an equal force in the opposite direction,* so the solid substrate exerts an equal force in the downward direction at the three-phase boundary. Interesting experimental evidence of this vertical force is shown by drops of liquids on elastic hydrogels—the drops actually pull the hydrogel upward at the periphery of the drop.[19]

Unlike Young, Willard Gibbs related the contact angle to the more familiar concept of surface energy. He proposed that the three-phase boundary line (between an insoluble solid and two fluids) would displace along the solid surface until it reached a point at which any further displacement of the line would create an increase in the free energy associated with the three-phase boundary line.[20] This condition of equilibrium reduces to

$$\gamma_{lv} \cos\theta = \gamma_{sv} - \gamma_{sl} \qquad (7)$$

which has the same form as Young's equation, but which employs surface energies instead of surface forces. While the student may feel more familiar with the language of surface energy, Gibb's derivation is usually not intuitively obvious. It also has the drawback (as does Young's derivation) that the derivation is done in two-dimensional space. Most classical textbooks on colloidal and surface chemistry derive Young's equation using free energy concepts and a differential change in contact area.[11,15]

A CONCEPTUALLY STRAIGHTFORWARD APPROACH

A straightforward approach to teaching the concept of contact angle and incomplete wetting is to combine the familiar rule that "a system moves to its state of lowest free energy" with a simple model of a liquid drop contacting a solid surface. Referring to the discussion of the spreading coefficient, we see that if

$$\gamma_{sv} < \gamma_{lv} + \gamma_{sl}$$

then the free energy of the system is not minimized at a state of complete spreading, and so the drop will not spread completely. The question now becomes, "How far must the drop spread to minimize the free energy of the system?" The answer is given by formulating the equation that describes the change in free energy: we simply subtract the energy "before" from the energy "after" the drop wets the surface. The surface energy before the drop contacts the surface is

$$\text{Total surface energy before} = S_T\gamma_{sv} + 4\pi r_d^2\,\gamma_{lv} \qquad (8)$$

where S_T is the total area of the solid surface and r_d is the radius of the drop. After the drop has contacted the surface, it spreads to form a spherical cap with a contact angle θ as shown in Figure 2. The total surface energy after the wetting of the drop is

$$\text{Total surface energy after} = (S_T - A_I)\gamma_{sv} + A_c\gamma_{lv} + A_I\gamma_{sl} \qquad (9)$$

where A_I is the area of the interface between liquid and solid, and A_c is the liquid-vapor interfacial area of the spherical cap of liquid. A_I and A_c are given by

$$A_I = \pi r_c^2\left(1-\cos^2\theta\right) \qquad (10)$$

and

$$A_c = 2\pi r_c^2(1-\cos\theta) \qquad (11)$$

where r_c is the radius of curvature of the spherical cap. The change in free energy of the system is found by subtracting Eq. (8) and Eq. (9)

$$\Delta G = 2\pi\gamma_{lv}\left(r_c^2(1-\cos\theta) - 2r_d^2\right) + \pi r_c^2\left(1-\cos^2\theta\right)(\gamma_{sl}-\gamma_{sv}) \qquad (12)$$

The minimum in free energy is found by equating to zero the derivative of Eq. (12) with respect to cos θ, and then solving for cos θ

$$\frac{d\Delta G}{d(\cos\theta)} = 0 = \pi\left\{2\gamma_{lv}\left[(1-\sigma)\frac{dr_c^2}{d\sigma} - r_c^2\right] - 2\sigma r_c^2(\gamma_{sl}-\gamma_{sv}) + \left(1-\sigma^2\right)(\gamma_{sl}-\gamma_{sv})\frac{dr_c^2}{d\sigma}\right\} \qquad (13)$$

where σ is a shorthand notation for cos θ. The spherical cap has constant volume

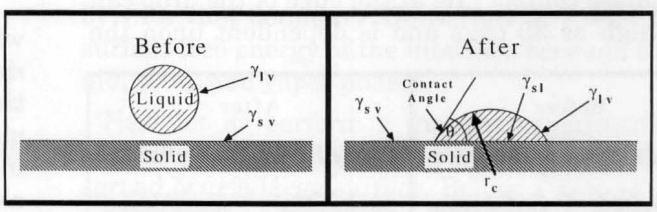


Figure 2. *Process of partial spreading of a liquid drop to form a spherical cap with radius r_c and contact angle θ on the solid.*

$$V = \pi r_c^3 \left(\frac{2}{3} - \sigma + \frac{\sigma^3}{3} \right)$$

so we can use implicit differentiation under conditions of constant volume to derive that

$$\frac{dr_c^2}{d\sigma} = \frac{2 r_c^2 (1-\sigma)^2}{2 - 3\sigma + \sigma^3} \qquad (14)$$

Combining Eqs. (13) and (14) and solving for σ gives

$$\sigma = \cos\theta = \frac{(\gamma_{sv} - \gamma_{sl})}{\gamma_{lv}} \qquad (15)$$

which is identical to Eq. (7).

DISCUSSION

This derivation contains several important points that the students should understand about wetting and contact angles. On the practical side, nearly all liquids partially or completely spread on solid surfaces. It is very rare to have a contact angle of 180° (no wetting). Equation (15) indicates that an angle of 180° would require $\gamma_{sl} = \gamma_{sv} + \gamma_{lv}$. This is rarely the case for aqueous solutions or organic liquids because the interfacial free energy usually has a value that is less than γ_{lv}. In the case of liquid metals (such as mercury) on organic solids, γ_{lv} and γ_{sl} are both so high that γ_{sv} becomes negligible and a contact angle of 180° is approached. This does not mean that "waterproofing" a porous surface is impossible. If the contact angle is greater than 90°, capillary pressure will resist the penetration of a liquid into a porous solid.

Another point on the practical side is that this derivation employed an ideal system that assumed the absence of gravity, surface roughness, surface contamination, surface chemical heterogeneity, surface mobility, liquid viscosity, line tension, or other real effects that often cause contact angles to depart from the contact angle predicted by Eq. (15).[21] These real complications and departures from the ideal case can often aid in understanding the nature of complex surfaces, but they are not the focus of this discussion. (More information on these topics can be found in references 17 and 21.) In some very clean and specialized experiments, all of these complications can be eliminated with the exception of gravity and line tension.

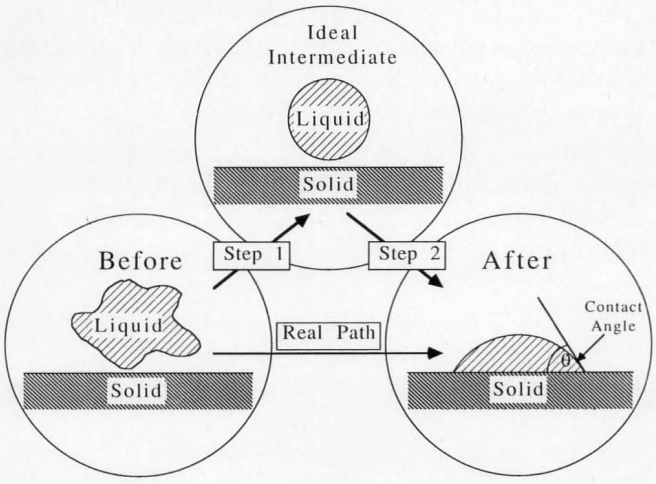


Figure 3. *Real and hypothetical ideal paths of an arbitrarily shaped liquid forming a spherical cap on a solid.*

If one cannot eliminate gravity and line tension effects in real measurements, one should at least understand what perturbations they may impose upon the theoretical contact angle. Gravity always distorts the drop shape from a spherical cap to an oblate spheroidal cap, but this distortion is negligible for sufficiently small drops. For example, with water on polyethylene, gravity distortion becomes noticeable if the drop volume is greater than about 2μl. This distortion causes the surface area of the cap (A_c) and the interface area (A_I) to increase over that of the ideal case.

Line tension is the one-dimensional analog to surface tension and can be defined as the excess free energy per distance at the three-phase boundary line between the liquid, solid, and vapor at the perimeter of the cap. Assuming that the free energy contribution from line tension is positive, a drop will not spread as far (compared to the case without line tension) before it reaches the minimum in free energy, and thus it will have a larger contact angle than predicted by Eq. (15). Both gravity and line tension contribute to the free energy of the system, and the net result upon equilibrium contact angle is still a subject of controversy.[22]

In the ideal case neglecting gravity and line tension, the contact angle is independent of the initial spherical drop size. The following argument also shows that contact angle is independent of initial drop shape; *i.e.,* a volume of liquid or arbitrary initial shape will form a spherical cap having Young's contact angle. Given that the resultant drop shape and contact angle is only a function of the free energy state, we can break the pathway of going from initial to final energy state into two hypothetical paths, neither of which may have actually occurred, but which represent the change in free energy states of the system (see Figure 3). The first path minimizes the free energy of the liquid shape by forming a sphere not yet in contact with the surface. The second step minimizes the free energy after the liquid sphere contacts the surface and results in a Young's contact angle according to the derivation presented above. Since both steps are minimizations

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MICROPROCESSOR-BASED CONTROLLERS

at Drexel University

D. R. COUGHANOWR
Drexel University
Philadelphia, PA 19104

In the United States, all chemical engineering curricula accredited by ABET (Accreditation Board for Engineering and Technology) must have a course in process dynamics and control. Very few students, however, have any exposure to modern industrial microprocessor-based control systems. During the past six years, the Department of Chemical Engineering at Drexel University has offered an elective course in advanced control which provides such exposure to these modern control systems. In the first phase of the development, we used Taylor MOD-30 controllers, but more recently, we have used Foxboro I/A (integrated automation) systems.

Many reasons are given for not providing students with hands-on experience on modern control systems: some faculty members who teach control believe that students need only a fundamental theoretical course and that a laboratory involving modern control equipment is unnecessary; other reasons include the high cost of the equipment and the complexity of the software. Furthermore, the vendors of control hardware and software have shown very little interest in trying to introduce their equipment into the laboratories of engineering schools. The author of this paper, however, believes that exposing students to modern industrial control equipment can be a valuable experience for them, that it motivates the application of control theory, and that the acquisition and use of such control equipment is financially feasible.

Donald R. Coughanowr *has been at Drexel University since 1967. Before coming to Drexel, he taught at Purdue University for eleven years. He received his BS degree from Rose-Hulman, his MS from the University of Pennsylvania, and his PhD from the University of Illinois, all in chemical engineering. His areas of research include process dynamics and control, aerosol technology and environmental engineering, diffusion with chemical reaction, and mathematical modeling.*

The emphasis in the course was on the use of the control hardware and software, while the use of mathematics was limited to stability calculations and tuning.

Our department offers a series of three courses in process control. They combine theory, applications, and laboratory experience, and make extensive use of digital computers to simulate and control chemical processes. The courses and the number of hours per week during a ten-week term are:

- 4.5 cr. Process Systems Engineering; 3 hr. lecture, 3 hr. laboratory
- 3 cr. Process Systems Engineering; 3 hr. lecture (graduate course)
- 3 cr. Applications of Computers to Control; 2 hr. lecture, 2 hr. laboratory

The first course, Process Systems Engineering, is required of all undergraduate students in chemical engineering and covers open-loop systems, closed-loop systems, stability, frequency response, and controller tuning. In the laboratory, the students simulate control processes with simulation software (TUTSIM) and operate a modern industrial microprocessor-based control system (Foxboro I/A system). It is also a prerequisite for the third course, Applications of Computers to Control.

In the second course (a graduate course), advanced topics such as stability, root locus, sampled-data control, multi-loop control (cascade, feed-forward, internal model control, etc.), and nonlinear control are covered.

The third course, Applications of Computers to Control, is an elective course which is primarily devoted to the study of a modern industrial microprocessor-based control system, and covers configuration, tuning, and operation of a Foxboro I/A system. Control applications include single-loop and multi-loop control systems.

A TYPICAL MICROPROCESSOR-BASED CONTROL SYSTEM

This paper will describe the use of the Foxboro I/A system in the graduate course Applications of Computers to Control. The equipment for the course was obtained with the help of an NSF grant from the program on Instrumentation and Laboratory Improvement. This grant, a 50-50 matching grant, provided three Foxboro systems. The 50% funding to match the NSF share came from industry, Drexel University, and a grant in the form of a discount from the Foxboro Company (the NSF program permits a discount from the equipment supplier to be part of the matching funds).

Each of the three control systems costs about $22,000 and consists of the following components:

- HP Vectra ES/12 Computer with 70 Mb hard disk, color monitor, mouse, and keyboard
- OK Data 80-column printer
- Local enclosure including power supply and two fieldbus modules (FBM) for communication with real processes: One FBM transmits 0-10 volt signals; the other 4-20 ma signals
- Allen Datagraph strip chart recorder

The equipment described above can be used to control a process which is either a simulated process in the computer or which is a real process connected through hard wiring to the fieldbus modules.

The Foxboro I/A system, which was first released in 1986, is a powerful distributed parameter control system which is able to control many loops of a complex industrial process. For the purpose of instruction in a university setting, the simplest version of the system, referred to as Personal Workstation for Fieldbus Interface (PW-FB), was purchased. The version used for a large plant would include several computers, a larger enclosure with more fieldbus modules, and more input/output devices (such as printers, monitors, operator input panels, etc.). The software provided in the simpler PW-FB system, however, is exactly the same as that used in the most extensive systems. Figure 1 shows the connections between the computer and the process for the PW-FB system. Foxboro provides different types of FBMs for analog signals and for digital signals. Each FBM can handle several inputs and outputs. Up to sixteen FBMs can be connected to the computer for the PW-FB system.

Each control system comes with a five-volume set of user's manuals. As with most manuals provided with complex equipment, their availability does not guarantee that one can simply hook up the components and begin using the equipment. Even though the software packages are loaded into the computer's hard disk at the factory and a field engineer from

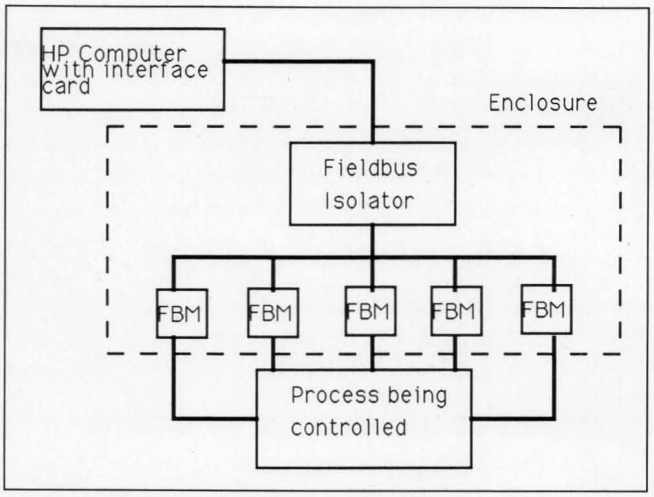

Figure 1. *PW-FB connections to process*

the company sets up the equipment, it is recommended that the purchaser attend one or two courses on using the equipment that are offered by the manufacturer. The Foxboro Company (among many other suppliers of control equipment), offers a wide variety of short courses that last from just a few days to several weeks. The author took two two-week courses on the Foxboro I/A system. The Foxboro Company also sells a training kit for the PW-FB system that consists of a manual, computer disks, and audio-visual tapes. This kit is very useful for self-study of the Foxboro I/A system.

The primary task of a microprocessor-based controller is implementation of a control algorithm; but the presence of a computer makes it possible to also assign a number of peripheral tasks that are useful in process control. Some of these tasks provided in a modern control system are to

- Implement classical and advanced control algorithms
- Provide static and dynamic displays on the monitor
- Provide process and diagnostic alarms
- Provide mathematical functions
- Provide data acquisition and storage (archiving)

More detail on the nature of these tasks can be found in Chapter 35 of Coughanowr.[1] The software to support all of these tasks is supplied by the manufacturer of the control equipment. In the Foxboro I/A system, these tasks are supported by the following seven software elements:

- Control subsystem
- Process display
- File utility
- Workstation environment
- System management
- Historian (optional)
- Spreadsheet (optional)

Only the first five elements are essential for using the system. The spreadsheet and historian elements were omitted at some savings in cost (they are considered luxuries in a university teaching laboratory). In an undergraduate laboratory course, the students need to use only the control subsystem and process display software. The teacher or laboratory technician will use the system management, file utility, and workstation environment software to set up the computer control system for laboratory experiments. Specific examples of the use of these three software elements for course development will be given later.

FEATURES OF THE FOXBORO I/A SYSTEM

All of the software for the Foxboro PW-FB system is stored on a 70-Mb hard disk. The control strategy for a control loop is configured by connecting several blocks together to form a structure called a compound. The connections are made by computer commands entered through the keyboard and mouse. There are about forty blocks available. A partial listing of the blocks (along with their names) is as follows:

- analog input (AIN)
- analog output (AOUT)
- conventional control (PID)
- control with self-tuning (PIDE)
- lead lag (LLAG)
- dead time (DTIME)
- switch (SWCH)

There are also blocks which process digital (or logic) signals (on/off) such as comparators, selectors, and timers which are needed for automatic plant start-up and shut-down and for batch operations.

Figure 2 shows that the block diagram for a compound for conventional single-loop control requires three blocks: AIN, PID, and AOUT. The AIN and AOUT blocks are used for converting and conditioning signals to and from the process for use in the computer. The PID block performs the control function. A compound for a cascade control system requires five blocks: two AIN, one AOUT, and two PID blocks.

One of the most important and complex blocks is the PID block, which has 81 parameters. Initially, one may be bewildered by the number of parameters to be set, but most of them can be left at their default values for a number of experiments. Many of these parameters are concerned with measurement alarms and limits on control variables.

One parameter that is common to most of the blocks is the sampling period, which can be varied

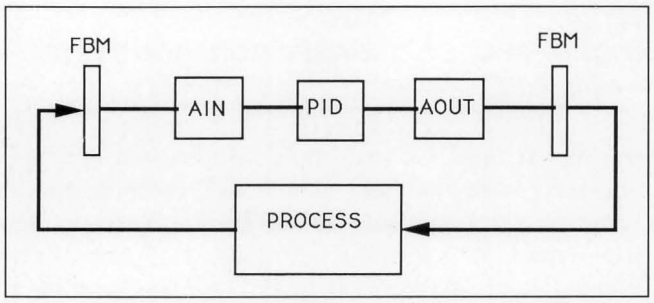

Figure 2. *Compound for single-loop control*

from 0.1 sec to 1 hr. For the PW-FB system, the lowest sampling period is 0.5 sec. Most of the experiments for the elective control course use a sampling period of 0.5 sec.

CONTENT OF THE ELECTIVE CONTROL COURSE

In the prerequisite undergraduate control course, the experiment using the Foxboro system is at the end of the course, after the student has studied tuning of closed-loop systems. It consists of using a pre-configured control law (PID) to tune a third-order system which is simulated on an analog computer. This limited experience stimulated enough interest that many students subsequently considered taking the elective control course, which covers the use of the Foxboro system in greater detail.

Because the elective course is limited to four hours per week for ten weeks, only continuous control blocks are used in the experiments. An outline of the course is shown in Table 1. In addition to the topics listed in the table, lectures are given on sampled-data control, implementation of practical control algorithms, multi-loop control strategies (cascade, feedforward, etc.), and process identification and tuning. Some knowledge of sampled-data control is needed in order to understand the difference between continuous control (pneumatic and electronic) and microprocessor-based (digital) control and the destabilizing effect of sampling on the stability of the closed-loop system.

In the lecture on the implementation of practical control algorithms, we discuss the use of external feedback to show how the integral action is obtained, which avoids reset windup. We also discuss a practical method used for obtaining a derivative action in which the measurement signal (not the error signal) is sent through a filter such as a lead-lag filter. The Foxboro software uses a Butterworth filter to obtain derivative action.

For years, one of the goals of control engineers has been to develop a device for automatically tuning a process on-line. Many suppliers of control hardware

now provide self-tuners; Foxboro's version is called EXACT, which stands for EXpert Automatic Control Tuning. The self-tuning algorithm, being proprietary information, is described only in general terms in the user's manual accompanying the control equipment. The lecture on system identification and tuning gives the students some idea of how the tuning algorithm may work, especially the pre-tune phase which analyzes an open-loop response. In this case, the Cohen-Coon tuning method is conceivably the approach used to obtain preliminary tuning parameters.

With the availability of modern computer control systems and their great variety of blocks (such as those mentioned above), the control engineer has for the first time the possibility of configuring complex control strategies which are limited only by his/her imagination and knowledge of the process. It is now feasible to implement advanced control strategies, such as Smith predictor control and internal model control, by blocks which simulate first-order, lead-lag, and transport lag transfer functions.

The configurators for creating displays are a very important part of the Foxboro software. The displays make it possible for the operator to observe the process variables and to control the process. In the elective control course, the students use the group display configurator since it is easy to use; they are not required to use the software (Display Builder and Display Configurator) which is needed to create elaborate dynamic displays showing flow diagrams of a process and which connect display objects (tank level, number fields, etc.) dynamically to block parameters and system variables. These process display configurators require too much time and effort and provide little educational benefit. Those experiments which use such process displays were configured in advance by the instructor.

TABLE 1
Applications of Computers to Control
2 hr. lecture, 2 hr. lab: 3 credits for 10 weeks

This course, which is primarily devoted to the study of a modern industrial microprocessor-based control system, covers configuration, tuning, and operation of a Foxboro (PW-FB) I/A system. Control applications include single-loop and multi-loop control systems.

1. Overview of microprocessor-based control system hardware and software
2. Tasks performed by a distributed control system: control algorithms, displays, alarms, mathematical functions, data storage, reports
3. Operation and control of a single-loop process using a Foxboro I/A control system; observe effect of sampling on stability
4. Configuration of control systems using various blocks
5. File utilities: storage and transfer of control data bases
6. Configuration of displays: detail, group, process
7. Alarms: system alarms, process alarms
8. Use of Foxboro I/A control system for Advanced Control Strategies: cascade, feedforward, internal model, self-tuning, *etc.*
9. System management: monitoring the state of control equipment

The experiments performed in the course are listed in Table 2 on the following page (with a brief description and the objective of each experiment). The emphasis in the course was on the use of the control hardware and software, while the use of mathematics was limited to stability calculations and tuning. Some students were pleasantly surprised to find a course in control that was not overburdened by mathematics, as is usually the case in the first course in control.

The experiments involved the control of processes simulated in the digital computer and processes simulated by an analog computer. The analog computer simulated process is considered a "real" process since 0-10 volt signals are transmitted to and from the analog computer through wires connected to the fieldbus module. A more realistic situation would be to control processes such as liquid-level, heat exchange, or pH, although such processes would require a substantial investment in measuring elements, control valves, and process equipment.

At the Foxboro training center, one of the laboratories uses with each microprocessor a process cart which holds a second-order liquid level system. If funds were available, such a process would provide the student with a more realistic view of the hardware components of a process control system. As a compromise, one such "real" process should be added to the laboratory. For those interested in using an analog computer for simulation of the process, Comdyna, Inc., of Great Barrington, Illinois, sells an 8-amplifier, 10-volt computer for about $2,000.

SUGGESTIONS FOR PLANNING A COMPUTER CONTROL LABORATORY

After acquiring the control equipment and the knowledge to use it, time must be found to develop interesting experiments that provide a balance between practice and theory. An excellent way to prepare laboratory experiments is to direct one or two students in a special projects course to develop and test several experiments. Laboratory outlines and some course notes on using the software must be written; the user's manuals are too detailed for use as course notes, although they can be used as a reference and should be available in the laboratory

TABLE 2
Applications of Computer to Control
Experiments for Foxboro I/A System

Experiment 1
- Control of tank level in a "get acquainted" experiment

In this experiment, the student uses a compound and displays which are already configured. The objective is to learn how to use the keyboard and a mouse to enter commands and parameters and to see the types of displays which can be provided by the software. The process being controlled is simulated in the digital computer using Foxboro blocks.

Experiment 2
- PI control of a third-order process simulated on an analog computer

In this experiment, a third-order system $[1/(\tau s+1)^3]$ simulated on the analog computer is controlled by a PID controller. The student tunes the controller by using Ziegler-Nichols rules. The time constant of the process, τ, is set to 4 seconds, with the result that the system responds quickly.

Experiment 3
- Configuration of a compound for PID control of a third-order process and configuration of a group display

The objective of this experiment is to learn how to use the control configurator software to devise a PID controller that controls a third-order process simulated on the analog computer. The same process of Experiment 2 is controlled.

Experiment 4
- Changes in configuration of compound of Experiment 3 (set point tracking, alarm parameters, *etc.*)

In this experiment the PID controller compound of Experiment 3 is modified to include process alarms, limits on process variables, and set-point tracking. The control system is operated to see that the system actually responds to the changes in configuration.

Experiment 5
- Control of a simulated process

To see that the process can be simulated by controller blocks in the computer, the student controls a process consisting of a first-order transfer function and a dead time.

Experiment 6
- Cascade control

This experiment shows how the control blocks can be configured for cascade control. The process controlled is a third-order system simulated on the analog computer. The student shows the benefit of cascade control by comparing the responses of cascade control and single-loop control of the same process.

Experiment 7
- PID control with PIDE block (self-tuning)

In this experiment, a PID block with self-tuning is used to control a third-order $[1/(\tau s+1)^3]$ process simulated in the computer. After obtaining preliminary controller settings with the pre-tune phase of the tuning algorithm, the process is placed on automatic and the closed-loop system is tuned on-line by introducing a sequence of step changes in set point. After about five changes in set point, the tuning parameters (PB, τ_I, τ_D) settle at values which are not too far from the tuning parameters calculated by Ziegler-Nichols rules. Watching the on-line self-tuning algorithm update the tuning parameters with each disturbance is fascinating.

for students to use. No more than two students should be assigned to a computer workstation. The use of the software can be learn-by-practice (trial-and-error) at the keyboard. If more than two people are assigned to a workstation, only the most assertive member of the group will learn much.

In addition to the usual tasks involved in running a laboratory, the instructor should reserve time for maintaining equipment and computer files. After a course is completed, the old files for compounds and displays must be deleted so that they do not get used by students when the course is offered again. It is also necessary to restore pre-configured compounds to their original form as required in some of the experiments, and master copies of files for compounds and displays must be saved. The file utility software is used to maintain files.

The workstation environment software is needed to develop new environments and to password-protect existing and new environments. An environment is a selection of "buttons" along the top menu bar of the monitor which is used by the operator to gain access to configurators, displays, compounds, and other software items. The Foxboro I/A system comes with some standard environments, such as "process operator's environment," "process control engineer's environment," etc. All of the environments can be prevented from being used by requiring a password to open an environment and all the features associated with that particular environment. In a course which has many inexperienced users, it may be advisable to password-protect all environments except those needed to perform the experiments. In this way, the corruption of files and system breakdowns will be reduced.

The use of commercially available microprocessor-based control systems in undergraduate courses at Drexel has been favorably received by the students. The first time the elective course was offered, more students registered for the course than could be accepted. Since there are only three Foxboro systems, enrollment was limited to six people per course section. If more time is available, more experiments could be introduced which involve complex multi-loop strategies and batch operation. Short courses using microprocessor-based controllers should be of interest to engineers in industry.

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FREE ENERGY OF WETTING

Continued from page 187.

in free energy, the total path represents a minimum in free energy, and Young's angle is the result.

In summary, when a liquid contacts a solid, either partial or complete wetting occurs. The extent of wetting is determined by a simple thermodynamic rule familiar to all students: the system will move to the state of lowest free energy. Although the rules are simple, the implications of the rules are profound and can have important consequences in many areas of applied chemistry.

ACKNOWLEDGMENTS

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REVIEW: HAZOP and HAZAN

Continued from page 167.

tive risk assessment" (QRA) or "probabilistic risk assessment" (PRA). This chapter includes very introductory material on calculating human risks and equipment reliability. There is an interesting section on calculating the cost of saving a life, demonstrating a huge range of cost values for various activities.

Chapter 4 is a manager's guide to hazard analysis and discusses the problems associated with hazard analysis in a managerial environment.

Chapter 5 discusses the most common objections raised against HAZOP and HAZAN, and the author provides a convincing case for applying these techniques.

Chapter 6 is a very short chapter which discusses sources of data and confidence limits, and Chapter 7 presents an interesting history of HAZOP and HAZAN.

I am a considerable fan of the author, Trevor Kletz, and buy all of his books as soon as they are published. He uses a powerful technique of mixing case histories with discussion to provide convincing cases for his material. Furthermore, he has a unique way of looking at things and often arrives at an "obvious" result that no one else even thought of.

The content of this book is introductory in nature and would be suitable for anyone with an interest in learning about basic HAZOP and HAZAN methods. It does not discuss techniques for decomposing large process units into suitable subunits for HAZOP analysis, a major problem for industrial practitioners, nor does it include some of the more recent organizational methods for managing a large HAZOP. There are some simple calculations related to equipment reliability, but nothing particularly difficult for chemical engineering students.

This book, along with Trevor's other books, would be a suitable reference or supplemental material for a chemical engineering design course or a course in chemical process safety. The students would be most responsive to the case histories and examples that are provided. ❐

Random Thoughts . . .

WHAT MATTERS IN COLLEGE

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

Most faculty lounge discussions of educational matters are not exactly models of rigorous logic. The "everyone knows" argument offered with no substantiation whatever is perhaps the most common gambit ("Student evaluations don't mean anything—everyone knows the highest student ratings always go to the easiest graders"), and the straight line through one data point is a close second ("Herman Frobish in Mechanical Engineering published eighteen papers last year and also won an outstanding teaching award, which proves that the best researchers are also the best teachers").

If you occasionally get into discussions about education and would like to buttress your arguments with something a bit more substantial, I recommend that you keep within easy reach a monumental work by Alexander Astin titled *What Matters in College.*[1] No single data point here! Astin collected longitudinal data on 24,847 students at 309 different institutions and determined the influences of a host of institutional characteristics on the students' college experience. The data include 146 input variables that characterize the entering students, including demographic measures, information about parental education and socioeconomic status, precollege academic performance measures, and self-predictions of a number of outcome variables; 192 environmental variables relating to institutional and faculty characteristics, including measures of the size and type of the institution, faculty demographics and attitudes, institutional emphasis on research, and the nature and extent of student-faculty and student peer group interactions; and 82 outcome variables, including measures of academic achievement, retention, career choice, self-concept, patterns of behavior, self-reported growth in skills, and perceptions of and satisfaction with the college experience.

Richard M. Felder *is Hoechst Celanese Professor of Chemical Engineering at North Carolina State University. He received his BChE from City College of CUNY and his PhD from Princeton. He has presented courses on chemical engineering principles, reactor design, process optimization, and effective teaching to various American and foreign industries and institutions. He is co-author of the text* Elementary Principles of Chemical Processes *(Wiley, 1986).*

Several results that I find particularly noteworthy are listed below. All of the cited correlations are positive (unless otherwise noted) and significant at a level $p < .0001$.

The quality of the college experience is strongly affected by student-faculty interactions. The frequency with which students talk with professors outside class, work with them on research projects, assist them in teaching, and visit their homes, correlates with student grade-point average, degree attainment, enrollment in graduate or professional school, every self-reported area of intellectual and personal growth, satisfaction with quality of instruction, and likelihood of choosing a career in college teaching.[1: 383-384]

A frequently debated issue is whether institutional size affects educational quality. Astin's findings indicate that smaller may indeed be better. Both smaller enrollments and lower student/faculty ratios correlate with satisfaction with instructional quality, enrollment in graduate school, interest in college teaching careers, and self-reported increases in overall academic development, cultural awareness, writing skills, critical thinking, analytic and problem-solving skills, leadership skills, public speak-

ing ability, and interpersonal skills.[1: 326-329] The better showing of smaller institutions is undoubtedly due in part to the greater incidence of personal student-faculty contacts at such institutions, suggesting the desirability of trying to increase such contacts at large universities.

Astin concludes, however, that as important as the student-faculty relationship may be, "...the student's peer group is the single most potent source of influence on growth and development during the undergraduate years."[1: 398] Frequency of student-student interactions (including discussing course content with other students, working on group projects, tutoring other students, and participating in intramural sports) correlates with improvement in GPA, graduating with honors, analytical and problem-solving skills, leadership ability, public speaking skills, interpersonal skills, preparation for graduate and professional school, and general knowledge, and correlates negatively with feeling depressed.[1: 385]

Many of the study findings specifically point to the benefits of cooperative learning—students working in teams toward a common goal. Frequency of group work has positive correlations with most areas of satisfaction, all self-ratings, and all areas of self-reported growth except foreign language skills. Tutoring other students—which may be done formally but also occurs in a natural way when teams of students work and study together—has positive correlations with all academic outcomes and with choice of careers in college teaching.[1: 387] As Astin notes:

> *Classroom research has consistently shown that cooperative learning approaches produce outcomes that are superior to those obtained through traditional competitive approaches, and it may well be that our findings concerning the power of the peer group offer a possible explanation: cooperative learning may be more potent . . . because it motivates students to become more active and more involved participants in the learning process. This greater involvement could come in at least two different ways. First, students may be motivated to expend more effort if they know that their work is going to be scrutinized by peers; and second, students may learn course material in greater depth if they are involved in helping teach it to fellow students.*[1: 427]

A number of results illustrate how emphasis on research at an institution affects the quality of that institution's instructional program. Astin's conclusion is that

> *Attending a college whose faculty is heavily research-oriented increases student dissatisfaction and impacts negatively on most measures of cognitive and affective development. Attending a college that is strongly oriented toward student development shows the opposite pattern of effects.*[1: 363]

A disturbing finding is that majoring in engineering correlates negatively with students' satisfaction with the quality of their instruction and overall college experience and positively with feeling overwhelmed and depressed. "Clearly, these findings indicate that the climate characterizing the typical institution with a strong emphasis on engineering is not ideal for student learning and personal development."[1: 360-361]

In the concluding chapters of the book, Astin proposes possible solutions to the educational quality problems raised by his study, suggesting that the first step is having an institutional leadership that understands the problems and is willing to do something to deal with them. "As long as faculty in the research universities are expected simultaneously to perform research, teaching, advising, university service, and outside professional activities, teaching and advising will continue to receive low priority." He proposes negotiated contracts with faculty members that would provide for a better institutional balance among the different functions of the professoriate.[1: 421] He also suggests that curricular planning efforts will pay off better if they focus less on formal structure and content and put more emphasis on pedagogy and other features of the delivery system.[1: 427]

This brief synopsis—which is intended only to whet your appetite—should raise all sorts of questions in your mind about the data and statistical methodology that led to the stated conclusions, how possible variable interactions and competing effects were accounted for, and what else Astin discovered. I encourage you to get the book and find the answers.

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THE ASEE CHEMICAL ENGINEERING DIVISION LECTURESHIP AWARD

Thirty-One Years of Recognizing Outstanding Achievement in Fundamental Chemical Engineering Theory or Practice

GEORGE BURNET
Iowa State University
Ames, IA 50011

The first time I heard a divisional lectureship suggested was during an informal discussion following a meeting of the AIChE Education Projects Committee at the Institute's 1962 national meeting in Chicago. In addition to this writer, Charlie Wilke and Max Peters were present. The discussion dealt with what could be done to strengthen the program of the Chemical Engineering Division of ASEE and to make membership in the Division more attractive to chemical engineering educators.

A number of suggestions were made, including joint ASEE/AIChE sessions at AIChE meetings, promoting the journal *Chemical Engineering Education,* emphasizing research administration and funding in programs at ASEE annual conferences, and increasing industrial participation.

It was Max Peters who first suggested an annual lectureship with the purpose of recognizing and encouraging outstanding achievement in an important field of fundamental chemical engineering theory or practice. A chemical engineering educator would deliver the lecture as part of the annual program of the Division. The idea was adopted quickly, and the Executive Committee of the Division proceeded to name Art Metzner as the first annual lecturer. The winner received a framed certificate in recognition of the lecture.

The annual lectureship proved to be popular and was well received. Attendance at the 1964 lecture exceeded 150 people. Publicity about the lectureship and each year's lecture was submitted to *Chemical Week, Chemical & Engineering News, Chemical Engineering Progress,* and *Chemical Engineering*, where news items and accompanying photographs of the lecturer were often published.

At the 1965 Annual Conference, the Executive Committee of the Division, under the chairmanship of John West, recommended that the annual lectureship become an award and that an industrial sponsor for the award be sought. This writer was asked to spearhead the effort, and a formal proposal was developed calling for an honorarium of $1,000, reimbursement of travel expenses, $300 for publication of the full text of the lecture in *Chemical Engineering Education,* and reimbursement to ASEE headquarters for the cost of administering the award.

In addition, the proposal identified the following accomplishments that were to be considered by the annual lectureship award committee in selecting the recipient.

1. *Achievement, through formulation or creative application of fundamental theory and principles, or important advances which have been accepted by colleagues and by others in the field of specialization, with promise of making further significant contributions.*
2. *Improvements of lasting influence to chemical engineering education through books, technical articles or laboratory or other teaching equipment, and demonstration of success as a teacher as well as the ability to inspire students to high levels of accomplishment.*
3. *Evidence of the ability to conduct original, sound, and productive research, personally or as a director of a research team, and to evaluate and report the significant results obtained.*
4. *Interest in furthering technical progress in chemical engineering through participation in professional and educational societies.*

The proposal further specified the duties and terms of service of an annual lectureship award committee and the information to be required in a nomination. Finally, it was noted that the award recipient would be required to submit a suitable manuscript based on the lecture to the journal *Chemical Engineering Education.*

Largely through the efforts of Wendel W. Burton, at that time Director of Employment for the 3M Company, 3M agreed to sponsor the award on a continuing basis. Mr. Burton had been active in ASEE for many years, having served most recently as its national treasurer.

In 1965, the Executive Committee of the Division endorsed the overall plan, and the proposal went simultaneously

to Glenn Murphy, ASEE Vice President for the Projects Operating Unit, Harold E. Heath, Chair of the ASEE Awards Policy Committee, and Leighton Collins, ASEE Executive Secretary. By May, 1966, the Division had authorization to proceed, and Octave Levenspiel was named the first 3M Lecturer. A book-size brochure containing information about the award, a list of previous lecturers, and biographical information of the recipient was widely distributed at the Annual Conference and was used in other ways to publicize the award.

The first lectureship award committee was appointed in 1966, and consisted of Robert Beckmann, Robert L. Pigford, and this writer. Over the next few years Joseph A. Bergantz, Andreas Acrivos, Myron Chetrick, and William Corcoran also served on this committee.

In 1973, Wendel Burton asked the Division to suggest ways the lectureship award could be enhanced to insure that its stature be maintained, and the following year a lecture tour by the awardee was implemented. Additional funds were provided by 3M to cover travel and subsistence to deliver the lecture at three universities during the academic year following its presentation at the ASEE annual conference. An additional honorarium of $500 was paid the awardee when the lecture tour was completed.

In 1989 the award was increased to $2,000, with a lecture tour honorarium of $1,000, and every fifth year the lecture has been presented at the ChE Division summer school. 3M continued its sponsorship of the award up to and including the 1991 annual conference.

During 1992 and 1993 the Division continued the award without an industrial sponsor. Expenses and a reduced honorarium were paid to the recipient, using funds from the Division treasury.

Thanks to the efforts of John Friedly, Chair of the Division for 1992-93, and Lewis Derzansky, University Relations Representative from Union Carbide, we will have the Union Carbide Lectureship Award beginning with the 1994 annual conference. The criteria, selection procedure, and responsibilities of the lecturer remain unchanged, the lecture will continue as a major event of the ASEE annual conference, and the full text of the lecture will be published in *CEE*. A lecture tour by the awardee remains as an option open to Union Carbide.

The lectureship award was the first and is still one of the most highly regarded of the twenty-one divisional awards. It is acknowledged as the premier award of the chemical engineering education community in the United States. A significant measure of the importance of the lectureship award lies in the prestige of its recipients. This list is a veritable "Who's Who" of chemical engineering education (see the boxed listing of winners). Twenty of the thirty-one recipients have been elected to the National Academy of Engineering, the highest professional recognition our country confers upon an engineer.

Much of the credit for the long and distinguished history of the award must go to the 3M Company for its encouragement, active participation in Division affairs, and financial support. The award has promoted quality and new advances in ChE education that have benefited the entire profession.

As we look to the future, we must note with approbation the commitment Union Carbide has made to a long-term association with the Lectureship Award. The rapid and challenging changes in science and technology will place increasing demands on chemical engineering education and practice. The lectureship award will continue to play an important role in meeting these demands. ❐

Editor's Note: *The 1992 Award Lecture, given by William N. Gill at the ASEE ChE Division Summer School in June of 1992, appears on the following pages.*

Chemical Engineering Division Lectureship Awardees

1963 Arthur B. Metzner; *Non-Newtonian Fluids*
1964 Charles R. Wilke; *Mass Transfer in Turbulent Flow*
1965 Leon Lapidus; *Aspects of Modern Control Theory and Application*
1966 Octave Levenspiel; *Changing Attitudes to Reactor Design*
1967 Andreas Acrivos; *Matched Asymptotic Expansion*
1968 L. E. Scriven; *Flow and Transfer at Fluid Interfaces*
1969 Cornelius J. Pings; *Some Current Studies in Liquid State Physics*
1970 Joe M. Smith; *Photochemical Processing: Photo-Decomposition of Pollutants in Water*
1971 William R. Schowalter; *The Art and Science of Rheology*
1972 Dale F. Rudd; *Synthesis and Analysis in Engineering*
1973 Rutherford Aris; *Diffusion and Reaction in Porous Catalysts*
1974 Elmer L. Gaden, Jr.; *Biotechnology: An Old Solution to a New Problem*
1975 John M. Prausnitz; *Molecular Thermodynamics for Chemical Process Design*
1976 Abraham E. Dukler; *The Role of Waves in Two-Phase Flow*
1977 Robert C. Reid; *Superheated Liquids: A Laboratory Curiosity and an Industrial Curse*
1978 Theodore Vermeulen; *Dynamics of Runaway Systems*
1979 Daniel D. Perlmutter; *A New Look at an Old Fossil*
1980 Klaus D. Timmerhaus; *Fundamental Concepts and Application of Cryogenic Heat Transfer*
1981 Arthur Westerberg; *Design Research: Both Theory and Strategy*
1982 Lowell B. Koppel; *Input Multiplicities in Process Control*
1983 Warren E. Stewart; *Simulation and Estimation by Orthogonal Collocation*
1984 TW Fraser Russell; *Semiconductor Chemical Reaction Engineering*
1985 Dan Luss; *Analysis and Modeling of Steady State Multiplicities*
1986 Robert S. Brodkey; *The Potential for Image Processing and Analysis in Turbulence Research*
1987 James J. Christensen; *Reflections on Teaching Creativity*
1988 Stanley I. Sandler; *Physical Properties and Process Design*
1989 J.L. Duda; *A Random Walk Through Porous Media*
1990 Brice Carnahan; *Computers in Engineering Education*
1991 Darsh T. Wasan; *Interfacial Transport Processes and Rheology*
1992 Willian N. Gill; *Interactive Dynamics of Convection and Crystal Growth*
1993 Morton M. Denn; *Polymer Flow Instabilities*

Award Lecture . . .

INTERACTIVE DYNAMICS OF CONVECTION AND CRYSTAL GROWTH

WILLIAM N. GILL
Rensselaer Polytechnic Institute
Troy, NY 12180-3590

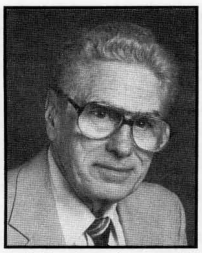
I would have liked this article to be the story of how basic theoretical and experimental breakthroughs have contributed to the spectacular advances in making and using new materials for the various "revolutions" we have witnessed since World War II. But it quickly became clear to me that the scope of such a story is beyond my competence to tell coherently. Therefore, I will attempt to give here a chemical engineer's view of some rather recent work on dendritic growth, which has generated many surprises over the last fifty years—only a part of the story I had hoped to tell.

The macroscopic properties of materials and the uses to which they can be put depend on their internal structure. In turn, the microstructure of materials depends on the details of the processes used to make them. Furthermore, the making of a material and its placement in a system for final use may occur simultaneously as, for example, with thin dielectric or metallic films made by chemical vapor deposition for integrated circuits. In this case, both the microstructure and the macrostructure (uniformity, absence of keyholes, step coverage, etc.) of the materials profoundly influence the performance of the devices which are made from them.

Microstructure and composition determine the properties of advanced materials, including alloy castings, polymer-ceramic composites, and films, and convection may profoundly affect all of them. The transport of energy and the redistribution of solute in the solidification of alloys are influenced by convection in different ways (depending on whether the transformation occurs in the vapor or liquid phase) because the transport properties differ enormously in gases and liquids.

The subject of interactive dynamics has very practical implications because it includes efforts to understand how process conditions, the microstructure, and macroscopic configuration of materials go together, as they are manufactured, to maximize their usefulness in various applications. If our goal is to create materials and structures with the properties we wish them to have, then an understanding of how to control the way they may be made to achieve this goal is of prime importance.

When crystals grow in a melt of pure liquid, from a solution of several components or from the vapor



William N. Gill *was presented with the Thirtieth Annual Chemical Engineering Division Lectureship Award for this lecture, which he gave at the ASEE ChE Division summer school meeting at Montana State University in August of 1992. The award is bestowed annually on a distinguished engineering educator and is designed to recognize and encourage outstanding achievements in important fields of fundamental chemical engineering theory or practice.*

Professor Gill is Russell Sage Professor in Chemical Engineering and the Center for Integrated Electronics at Rensselaer Polytechnic Institute, and has been a faculty member at Syracuse University, Clarkson University, and the State University of New York at Buffalo. He served as chairman of the ChE departments at Clarkson and RPI, Dean of Engineering at Buffalo, Fulbright Senior Research Scholar in England and Australia, and Glenn Murphy Distinguished Professor at Iowa State.

Gill's research has focused on several areas, including turbulent convection, Taylor diffusion, membrane separations, and various aspects of crystal growth. His contributions are summarized in more than 150 articles balanced between theoretical and experimental content. His motivation is the understanding of chemical and physical phenomena that underlie processes of practical importance from both industrial and environmental viewpoints. His work has been cited about 2000 times in a large number of journals and books in many fields, including medicine, biophysics and biochemistry, chemistry, geophysics, applied mathematics, condensed matter physics, virtually all areas of engineering, and materials science.

He has investigated the effects of concentration polarization, the interaction among components in the feed, ways to model hollow fiber and spiral wound systems, and the fundamental processes that underlie transport in membranes. His most recent area of interest has been crystallization, including dendritic growth and rapid solidification, and currently with chemical vapor deposition of copper and interlayer dielectric films for integrated circuits.

Gill has worked with many graduate students and has been thesis advisor to thirty-one PhD recipients. These former students currently have faculty positions at universities in the United States, Israel, Korea, Taiwan, India, Iran, and Europe. He has been editor of Chemical Engineering Communications *since 1979 and serves on several boards.*

The subject of interactive dynamics has very practical implications because it includes efforts to understand how process conditions, the microstructure, and macroscopic configuration of materials go together . . . . If our goal is to create materials and structures with the properties we wish them to have, then an understanding of how to control the way they may be made to achieve this goal is of prime importance.

phase by deposition on a substrate, an interface is created, the shape and movement of which depends on the conditions that prevail on both sides of the interfacial region and within that region itself. In other words, the movement and shape of the interface creates an active pattern which evolves in time and which is inherently three-dimensional in systems of practical interest. The quantitative description of this spontaneous nonlinear dynamic process is one of the objectives of the theory of pattern formation, and one particular aspect of it includes the interactive dynamics of convection and crystal growth. Convection is coupled with the growth of the crystals involved, and each affects the other because of the movement of the mobile interface.

The problems associated with studying interactive dynamics are formidable, but progress is being made which will contribute to the development of some of the extraordinary materials of the future. The October 1986 issue of *Scientific American* contains thirteen articles, well worth reading, on various aspects of the development of materials, providing an interesting perspective on the modern aspects of materials engineering and science by people who are not chemical engineers. A physicist's viewpoint on dendrites and the theory of pattern formation is given by J.S. Langer in *Science* (March 1989); this perspective was updated with his more recent article in *Physics Today* (October 1992) in which he appealed for a rational approach to materials research on the national level.

An applied mathematician's viewpoint on interactive dynamics in crystal growth is given in two review articles published recently by Huppert[1] and Davis[2] in the *Journal of Fluid Mechanics.* Brown,[3] a chemical engineer, has reviewed various interesting aspects of single semiconductor crystal growth from the melt, especially for electronic and optoelectronic devices.

The *Handbook of Crystal Growth* (Edited by Hurle; Elsevier, 1993) contains a number of chapters which review subjects related to this one. Also, a conference was held in March of 1992 in Chamonix, France, the papers from which have been published as *Interactive Dynamics of Convection and Solidification* (Kluwer Academic Publishers, edited by Davis, *et al.*).

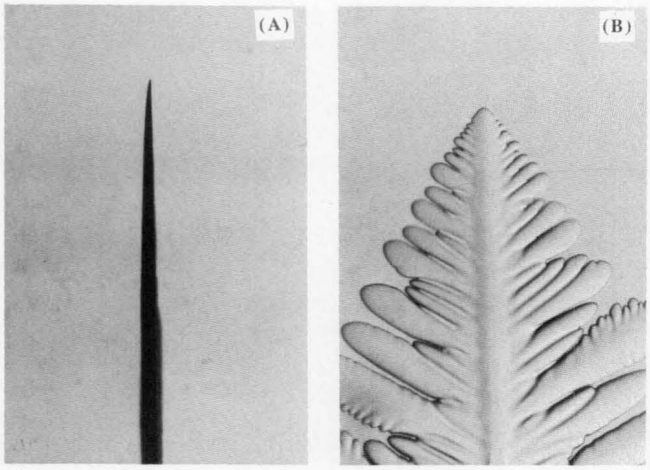


Figure 1. *Photographs of an anisotropic ice dendrite with $\Delta T = 0.6°K$, $R_2/R_1 \sim 28$, magnification 26x:*
(A) edge view with tip radius, R_1;
(B) Basal plane with tip radius, R_2.

When they are still undergraduates, chemical engineers begin learning to deal with heat, mass, and momentum transport coupled with chemical reactions in the bulk phase or on the boundaries of the system. At Rensselaer, for example, individual courses in fluid mechanics, heat transfer, separation processes, and chemical reactor design are required in the third and fourth years of the undergraduate program. The exposure to separation processes, reactor design, and the option to take a fourth-year course in transport phenomena provides a good foundation for graduate-level course work and research in materials processing.

THE ROLE OF TRANSPORT PROCESSES IN CRYSTAL GROWTH

It is important to understand the roles of heat, mass, and momentum transfer in crystal growth processes. One or more of these phenomena may be of crucial importance, depending on the phase change system involved and how the process is carried out. To illustrate this, we will consider dendritic growth which, according to Glicksman and Marsh,[4] is the most prevalent form of solidification.

In the simplest case involving dendrites, the free growth of crystals (unencumbered by walls) from pure undercooled melts produces dendritic structures

in which the leading tip of the main stem of the dendrite propagates in the preferred crystallographic direction, as shown in Figure 1. These reproducible patterns have small dimensions and large curvature. They seem to occur in nature due to the competition among the kinetic resistance to the attachment of molecules at the surface, the effect of the surface energy of the solid-liquid interface, and the rate of removal of heat from the surface into the subcooled melt. The underlying reasons for why dendrites form the patterns they do are not completely clear and currently are being investigated on a worldwide basis. Figure 1 illustrates how different ice dendrites appear when viewed from the basal plane, where one sees a rich sidebranch structure, and from the edge plane, which has no sidebranches at all. Figure 2 shows the typical shape of a water drop in equilibrium with the ice matrix in which it is encased. This drop also demonstrates strong anisotropy.

Surface tension depresses the melting point of an interface which is convex to the melt, and attachment kinetics reduce the driving force for heat transfer, both of which stabilize the solidification front. The rate of heat removal by conduction to the undercooled melt may be influenced significantly by thermal or forced convection, which will have an effect on the properties of the crystal. A successful theory of this seemingly straightforward problem from which one hopes to predict the size, shape, and growth rate of the crystal, has proved to be elusive.

Grain size (and its distribution in a material) is one of the properties that is of importance in crystal growth processes, ranging from the making of steel to the deposition of thin metallic films in integrated circuits. Within each grain of a structural material (such as a titanium-based alloy) is a microstructure formed by dendritic growth. The microstructure consists of a pattern in which the interstices between the main stems and the sidebranches of alloy dendrites are filled with material which is rich in solute. The solution in the interstices solidifies more slowly than that contained in the dendrites. This microstructure determines many of the macroscopic properties of structural materials, and thus the uses for them. Therefore it is of major importance to understand how to control the rate of dendritic growth, the size of the dendrites, and the spacing between their sidebranches.

It has been known for a long time that processing techniques can have a profound influence on the microstructure of materials. Indeed, the basic ideas regarding some of the methods currently used to produce exotic materials, such as directional solidification, modified directional solidification to produce single crystals, and rapid solidification, had their roots in the 1960s. These processing methods have had a major impact on the development of advanced structural materials because they influence the microstructure in predictable ways. Furthermore, the methods used are all related to controlling the transport processes involved in the making of these materials.

Examples of the dramatic improvements in materials due to the procedures used to process them abound. The use of directionally solidified metal structures has resulted in an increase of 150°C to 200°C in inlet temperatures for turbines, which substantially increases their efficiency. One can actually obtain amorphous metal alloys by rapid solidification, and these have properties which may substantially reduce the energy losses which occur in the distribution of power. Thus it is important from both a basic and a practical viewpoint to understand the role of various transport mechanisms in determining rates of production, the length scales that correspond to the rates of production, and how a particu-

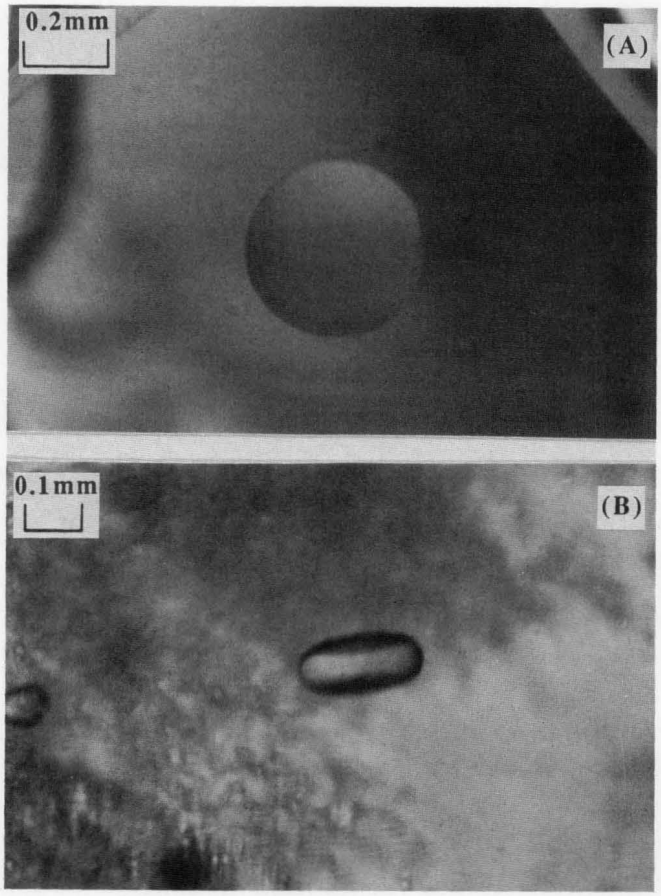


Figure 2. *Equilibrium shape of highly anisotropic water drop in ice matrix: (A) basal plane; (B) edge plane.*

Convection is the organized movement of large groups of molecules on a macroscale, and (as required by Newton's laws of motions) it results from force fields which may be subtle and difficult to manipulate or control.

lar growth path is selected, which determines what the length scales and rates are. Here, I will concentrate on some of the ways natural and forced convection affect the crystal growth process—it is a subject on which some of my students and I have spent a considerable amount of time.

CONVECTION AND CRYSTAL GROWTH

Convection is the organized movement of large groups of molecules on a macroscale, and (as required by Newton's laws of motions) it results from force fields which may be subtle and difficult to manipulate or control. For example, flow may be caused primarily by buoyancy forces which are ubiquitous on earth due to its gravitational field. If one uses the microgravity levels offered by a space station to reduce gravity by several orders of magnitude, surface tension forces may become more important than gravity in determining the nature of the flow and, therefore, in materials processing. Also, convection may be useful in enhancing heat and mass transfer rates and in reducing processing time. Or it may adversely affect product uniformity, as can happen in the chemical vapor deposition (CVD), of thin films in a flow field that is not oriented properly.

Essentially, all of the mathematical work aimed at understanding the role of convection in dendritic growth has dealt with needle crystals in which the sidebranches are neglected and one concentrates on the region near the tip of the dendrite. The first exact solution for the growth of a dendrite from the melt was obtained by Ivantsov almost fifty years ago. His classical analysis applied to isothermal needle crystals growing in a stationary melt with zero velocity, $\overline{U} = 0$. Some of the work my students and I have done has focused on trying to add a realistic description of convection in the melt to generalize Ivantsov's analysis. Thus, Dash and Gill[5] showed that a similarity variable could be used to solve the energy equation given by

$$\frac{\partial T}{\partial t} + \overline{U} \bullet \nabla T = \alpha \nabla^2 T \qquad (1)$$

for an isothermal needle crystal including convection in the melt, if the velocity field $\overline{U}$ in the convective term $\overline{U} \bullet \nabla T$ on the left-hand side of Eq. (1) is given by the Oseen or potential flow models.

Ananth and Gill[6] and Saville and Beaghton[7] for Oseen flow, and Ananth[8], and BenAmar, *et al.*,[9] for potential flow, used variations on the similarity approach to study the growth of parabolic dendrites. Ananth and Gill considered the growth of crystals in the form of an elliptical paraboloid and gave exact solutions to the Oseen flow and energy equations in an effort to understand better the growth of ice crystals which are anisotropic. The body shapes, flow fields, and thermal fields which yield self-consistent solutions for the steady growth of dendrites into a melt which itself is in motion, $\overline{U} \neq 0$, were determined by Ananth and Gill. Among surfaces of revolution only a parabolic crystal grows steadily, and either the Stokes flow, Oseen viscous flow, or potential flow approximations must be made in order to obtain an exact solution for the growth Peclet number

$$P_G = \frac{V_G R}{\alpha}$$

where V_G is the growth velocity, R is the tip radius, and α is the thermal conductivity of the melt. Stokes and potential flows are valid in the limit

$$Re = \frac{UR}{\nu} \to 0 \quad \text{and} \quad Re \to \infty$$

respectively. As discussed by Lagerstrom and Cole[10] and Lagerstrom,[11] the Oseen approximation to the Navier-Stokes equations is uniformly valid for a semi-infinite three-dimensional paraboloid of revolution at very small Reynolds numbers.

The growth of shape-preserving (near the tip) dendrites in subcooled melts has been observed experimentally in detail for succinonitrile (SCN) by Huang and Glicksman[12] and for ice by Fujioka,[13] Tirmizi and Gill,[14] and Koo, *et al.*[15] In these experiments crystals grow from a capillary tube into a melt which is quiescent. Near the crystal-melt interface, however, there is a natural convection flow generated by gravity acting on a density distribution created by the temperature gradients, caused by the spreading of the heat of fusion into the melt. The intensity of this natural convection is indicated by the Grashof number, Gr.

In order to compare their Oseen flow solutions to experimental data on the dendritic growth of SCN, Ananth and Gill interpreted $Re = \sqrt{Gr}$ and showed reasonable agreement with the data of Huang and Glicksman. They found that the Grashof number increases as undercooling, ΔT, which is the driving force for the flow, decreases. This counter-intuitive result occurs because the length scale, R, which appears as R^3 in

$$Gr = \frac{\beta g \Delta T R^3}{\nu^2}$$

increases as ΔT decreases in the experiments on SCN. Koo, *et al.*, demonstrated that the same behavior is observed with ice dendrites if one uses the harmonic mean

$$R_m = \frac{2 R_1 R_2}{R_1 + R_2}$$

of the tip radii, R_1 and R_2 of the edge and basal planes as the length scale. This result is shown in Figure 3, and Gr is seen to change by several orders of magnitude. Ananth and Gill also solved approximately the fully nonlinear thermal convection problem, where Gr arises naturally, and they demonstrated excellent agreement between the mathematical results and the data on SCN. Subsequently, Canright and Davis[16] studied the limiting case of the effect of very weak buoyancy driven flows on the shape of dendrites and showed that their analysis was complementary to that of Ananth and Gill.

THEORIES OF SELECTION IN DENDRITIC GROWTH

The experiments mentioned above all show that the growth velocity, V_G, and the tip radius of the dendrite, R, are determined uniquely when the undercooling, ΔT, is fixed. In contrast, Ivantsov's pure conduction solution indicates that the Peclet number, P_G, is fixed when the dimensionless undercooling given by the Stefan number, St, is specified. Consequently, only the product, $V_G R$, is determined by fixing ΔT, and the individual values of V_G and R cannot be predicted. Thus, the theory is incomplete if one assumes that the dendrites are isothermal and smooth.

If one includes natural convection, or forced convection, V_G increases and R decreases, but the same degeneracy exists in the theory. Therefore considerable effort has been expended over many years to find a selection criterion for V_G and R, and these efforts in one way or another revolve around the introduction of surface tension in the problem. The selection criterion is an additional relationship between V_G and R which enables each of them to be chosen uniquely for given values of ΔT and U_∞.

Until the middle of the 1970s, the maximum-velocity hypothesis was used for this purpose, and it assumed that the operating point was the maximum in the V_G versus R curve. This assumption was used for about thirty years until it was shown to be incorrect by the careful experiments on succinonitrile of Glicksman, *et al.*,[17] in which both V_G and R were measured as a function of ΔT with $U_\infty = 0$.

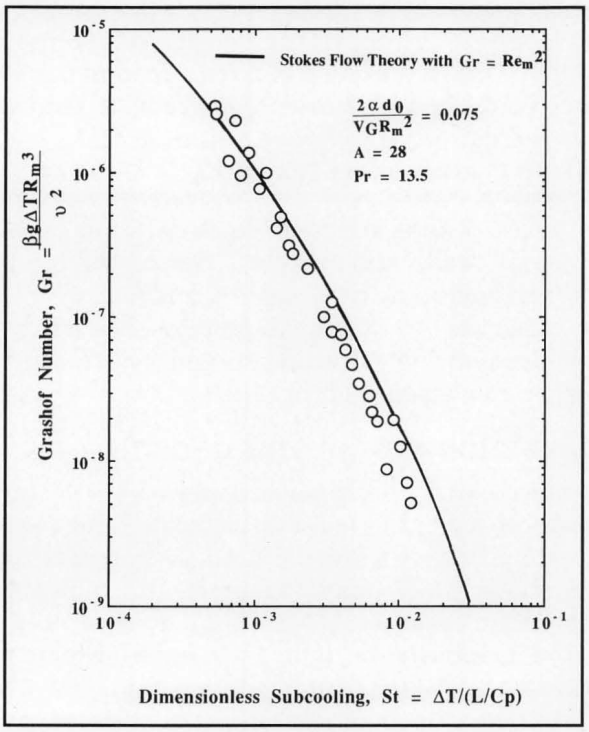


Figure 3. *Use of thermal convection analogy, $Gr = Re^2_m$, with selection parameter, $\sigma^* = 0.075$ to estimate level of natural convection. Comparison of Grashof numbers observed experimentally with those predicted by Stokes flow theory.*

Then Langer and Muller-Krumbhaar[18] proposed the marginal stability theory based on the introduction of surface tension as a perturbation. This led to the relationship

$$\sigma^* = \frac{2 d_o \alpha}{V_G R^2} = \text{constant} \qquad (2)$$

where

d_o = $\gamma T_m C_p / L^2$, the capillary length
α = thermal diffusivity
γ = surface tension
T_m, C_p, L = melting point, heat capacity, heat of fusion

The notion that $V_G R^2$ is independent of ΔT also had been proposed by Oldfield[19] on the basis of computer experiments in which he balanced the heat transfer by conduction against the stabilizing effect of surface tension.

More recently the selection of the growth velocity and length scale in the absence of fluid flow has been addressed in many articles which discuss the microscopic solvability theories. For detailed reviews of this work I refer the reader to the work by Langer[23] and Kessler, *et al.*[20] They showed that no solutions can be found in the presence of finite surface tension unless anisotropic effects (variation in surface tension around the surface of the crystal), no matter

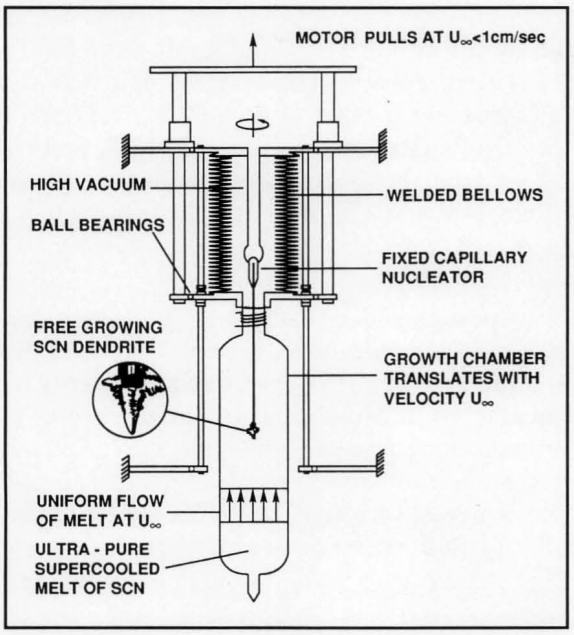


Figure 4. *Forced convection growth cell provides rigid body motion of melt with dendrite fixed in space.*

how small, are taken into account, and that the fastest growing tip is selected because it gives the only dynamically stable solution.

Anisotropy refers to the variation in surface tension around the dendrite in the azimuthal direction. When the anisotropy, ε, is about 0.5%, the microscopic solvability theory yields according to Mushol, *et al.*,[21] a result which is given by

$$\sigma^* = \frac{2\,\alpha d_o}{V_G R^2} \sim 0.01$$

This result is smaller by a factor of two than that obtained from the marginal stability hypothesis of Langer and Muller-Krumbhaar which neglects the anisotropic effects. Both theories are in qualitative agreement with the experimental value of $\sigma^* \sim 0.02$ for the data on succinonitrile of Huang and Glicksman, and Lee, *et al.*,[22] when the subcooling is large and the effect of convection is small.

The agreement between microscopic solvability theory (MST) and the experiments for succinonitrile was encouraging, and it led to a feeling that real progress was being made in our understanding of dendritic growth. But Langer,[23] who is an original contributor to MST, raised warning signals several years ago, indicating that the predictions of MST had not been confirmed experimentally. Unfortunately, the experimental evidence which has been accumulating lately on different materials does not seem to be consistent with MST and suggests that Langer's concerns were well founded.

SOME EXPERIMENTAL TESTS OF SELECTION THEORIES

Two types of experiments yield results which are significantly different from those predicted by MST. I will try to describe both of these experiments, but I will concentrate more on the forced convection experiments carried out by my research group. Because we had worked on the theoretical problem of including forced convection in the melt, my students and I naturally were interested in performing experiments under conditions which corresponded as closely as possible with the assumptions we made to obtain forced convection solutions of Eq. (1).

Forced convection experiments seemed attractive because they introduced the velocity of the melt at a large distance from the crystal, which is a new quantity, U_∞, that can be varied independently of ΔT. As usual, these experiments proved to be more difficult and time consuming than we originally thought they would be.

First, we wanted to study a material whose properties were well known so that we could reproduce previous results for $U_\infty = 0$ before attempting to do something entirely new. *Second*, the material (succinonitrile) which we settled on had to be ultrapure (99.999% or better) and was extremely expensive at the time. Therefore we had to think small in designing an apparatus. *Third*, we realized that our forced convection velocities, U_∞, would have to be very well defined and large enough to render natural convection negligible. *Fourth*, the melt had to be transparent because we wanted to track the crystal-melt interface and measure precisely both the growth rate and the tip radius in real time. *Fifth*, we would have to photograph and make video tapes of the experiments to enhance our understanding of the physical processes involved. *Sixth*, we would have to control the temperature of the growth cell to extremely close limits. The solutions to these and other problems are described in a thesis by Lee[24] which had significant contributions by Ananth (who was working with me as a post doc at the time).

In forced convection experiments on crystal growth, one has to deal with three different velocities: V_G, U_N, and U_∞. It is important to understand clearly the meaning of each because they all exist simultaneously. In our experiments we observed the shape of the interface of the dendrite which we characterize by the tip radius, R, the motion of the interface denoted by the velocity V_G, and the velocity of the melt with respect to a fixed frame of reference, U_∞. We could not observe or measure the velocity due to natural convection, U_N. Therefore we used theory to

estimate it and conducted our experiments so that U_∞/U_N and U_∞/V_G ranged up to about 40 and 300, respectively, as indicated by Gill, *et al.*[25]

The apparatus in which the forced convection experiments were carried out is described in detail by Lee[24] and is shown in Figure 4. The basic idea is to keep stationary the capillary from which the crystal emerges and to have the cell containing about 100 cm^3 of SCN move so that it creates a rigid body motion of the melt relative to the crystal over the range $0 \le U_\infty \le 1$ cm/sec. The cell is operated in a constant-temperature bath which is controlled to ±0.001 K, and after purification the SCN remains hermetically sealed throughout the experiments. The patterns formed by the dendrite-melt interface are observed through a microscope and recorded on video film. The measurements of V_G and R deviated from their mean values by less than 2.5% and 5%, respectively.

The goals of this work were to measure various characteristics of the dendrite, including V_G, R, distance from the tip to the first sidebranch, distance between sidebranches, and other quantities, as functions of the undercooling, ΔT, and the forced convection velocity, U_∞, which can be varied independently. However, here I shall discuss only the steady state measurements of V_G and R and their implications when they are combined to obtain σ^*, which is defined in Eq. (2). In this way we can obtain

$$\sigma^* = \sigma^*(\Delta T, U_\infty) \tag{3}$$

The results obtained by Lee, *et al.*,[22] show that V_G increases and R decreases monotonically with both ΔT and U_∞. All four of the quantities (V_G, R, ΔT, and U_∞) were measured in our experiments. Therefore we were able to determine if V_G increases more or less quickly than R^2 decreases, and this shows how $V_G R^2$ behaves either with ΔT or U_∞. In this way one can establish experimentally the behavior of the selection parameter, σ^*, as a function of (ΔT, U_∞).

By determining the dependence of σ^* on (ΔT, U_∞), we can test one of the basic predictions of microscopic solvability theory. Bouissou and Pelce[26] used microscopic solvability theory to calculate this dependence, and they reported that σ^* **decreases** with **increased** (U_∞/V_G), which is the opposite of what the experiments of Gill, *et al.*,[25] and Lee, *et al.*,[22] show. Figure 5 displays the measured values of σ^* as a function of U_∞/V_G.

In Figure 5 we see that σ^* **increases** by more than 50% as U_∞/V_G **increases**, as shown by Gill, *et al.*[25] Since this behavior is contrary to that predicted by the two-dimensional analysis of Bouissou and Pelce, it appears that microscopic solvability theory does not predict even qualitatively the correct dependence of σ^* on U_∞ for SCN. A more dramatic contrast between theory and experiment is shown by Lee, *et al.*,[22] in their Figure 4 in which the slope of the data is negative and opposite to the prediction of MST.

Let us now consider the growth in quiescent melt of dendrites other than SCN and attempt to determine if MST predicts the proper dependence of σ^* on the anisotropy, ε. Muschol, *et al.*, made careful measurements of ε, and we shall outline briefly only their results and the information needed to understand them qualitatively. The Gibbs-Thompson equation for a cubic crystal can be written

$$T_i = T_m[1-(\gamma+\gamma_{\theta\theta})\kappa/L] \tag{4}$$

where

- γ surface tension
- $\gamma_{\theta\theta}$ second derivative of γ with the angular coordinate, θ
- θ measures position around the surface of the dendrite
- κ total curvature
- L heat of fusion
- T_m melting point of a flat surface
- T_i local interfacial temperature

If the surface tension is represented by

$$\gamma = \gamma_0[1+\varepsilon_m \cos m\theta] \tag{5}$$

combining Eqs. (4) and (5) obtains the approximation

$$T_i = T_m - \frac{2\gamma_0 T_m}{RL}[1-\alpha\cos m\theta] \tag{6}$$

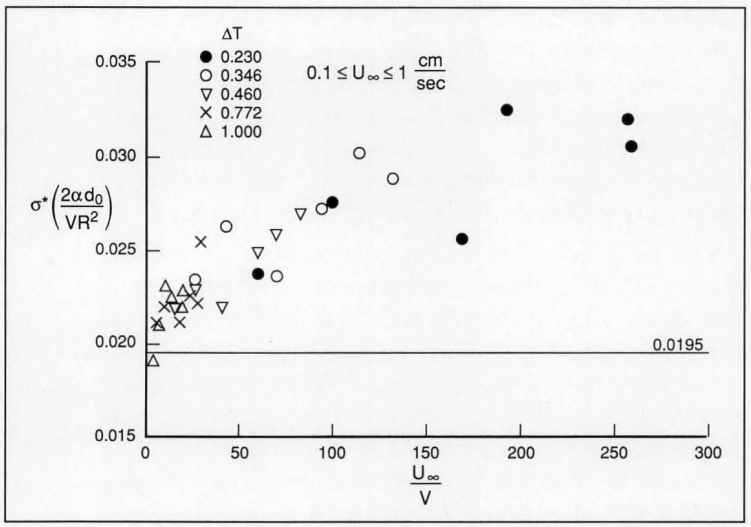


Figure 5. *Selection parameter, $\sigma^* = (2\alpha d_o)/(V_G R^2)$ for SCN dendrites increases by more than 50% as ratio of forced convection velocity, U_∞, to growth velocity, V_G, increases.*

where

R mean value of the tip radius

α anisotropy factor used by Mushol, *et al.*[21]

In Eq. (5), α is related to ε_m by $\alpha = (m^2-1)\varepsilon_m$. As pointed out by Glicksman and Marsh, (who subsequently made similar comparisons to those of Mushol, *et al.*) Eq. (6) shows that the equilibrium melting point at a point on an anisotropic solid-liquid interface depends on both its curvature and the orientation of the interface normal with respect to the principal crystallographic axes.

Mushol, *et al.*, computed theoretical values for the selection parameter, σ^*_{th}, based on various MST analytical models and numerical codes for materials for which α had been measured. The results were disappointing, and they concluded (as did Glicksman and Marsh) that the predictions of MST do not agree well with the available experimental evidence for dendrites grown in quiescent melts. Therefore, it seems that both forced convection experiments ($U_\infty > 0$) with SCN[22,25] and experiments on the relationship of σ^* with ε for other materials including alloys, do not support MST. It would appear that something fundamental is missing from the theory.

CONCLUDING REMARKS

Where does this leave us? Where do we go from here? It is obvious that great progress has been made in developing new materials, and this progress has been aided and abetted by a continually expanding body of experimental and theoretical knowledge about crystal growth. Furthermore, the available experiments have been getting more precise, which is important when testing new ideas and insights. Indeed, one can expect that as new experiments accumulate, they will suggest new theoretical concepts, as has been the case in virtually all fields of science. Also, incredibly fast computers and intriguing mathematical methods have been developed which will facilitate the integration of theory and experiments.

It is impossible to predict just when a fully satisfactory, predictive theory of dendritic growth will be available. I doubt it will take another 350 years, as apparently has been required to prove Fermat's last theorem. When it arrives, new doors no doubt will open up, and it probably will be helpful in controlling the microstructure of even more useful and exotic materials. In the meantime, there is a need for precise experiments on multicomponent materials of practical importance. Based on past experience, I think such experiments will stimulate new developments of technological importance—and deeper theoretical understanding as well.

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ChE *class and home problems*

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

THERMODYNAMICS AND COMMON SENSE

OCTAVE LEVENSPIEL
Oregon State University
Corvallis, OR 97331-2702

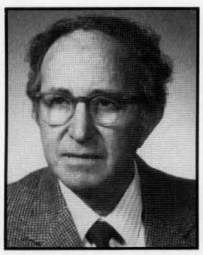
Though it is one of science's grandest pure-logic structures which awes and enraptures its faithful, thermodynamics unfortunately causes much grief for the student who is studying the subject.

Why?

Let's look at a simple situation—that of a batch system of internal energy U going from state 1 to state 2. Here we see written in all texts

$$\Delta U = Q - W \qquad (1)$$

But if the system is raised or lowered (potential energy change, ΔE_p), speeded or slowed (kinetic energy change, ΔE_k), or swelled or shrunk (expansion work, W_{pV}) then the above first law expression becomes more generally



Octave Levenspiel *is author of four chemical engineering texts. One of them is over thirty years old but is still widely used and has been translated into ten languages. Another, his favorite and funniest, is practically unknown today. Octave is now a retired (emeritus) professor, emjoying himself and struggling to understand thermodynamics.*

$$\Delta U + \Delta E_p + \Delta E_k = Q - W_{shaft} - W_{pV} \qquad (2)$$

Clear?

Do you accept this?

Yes?

GOOD!

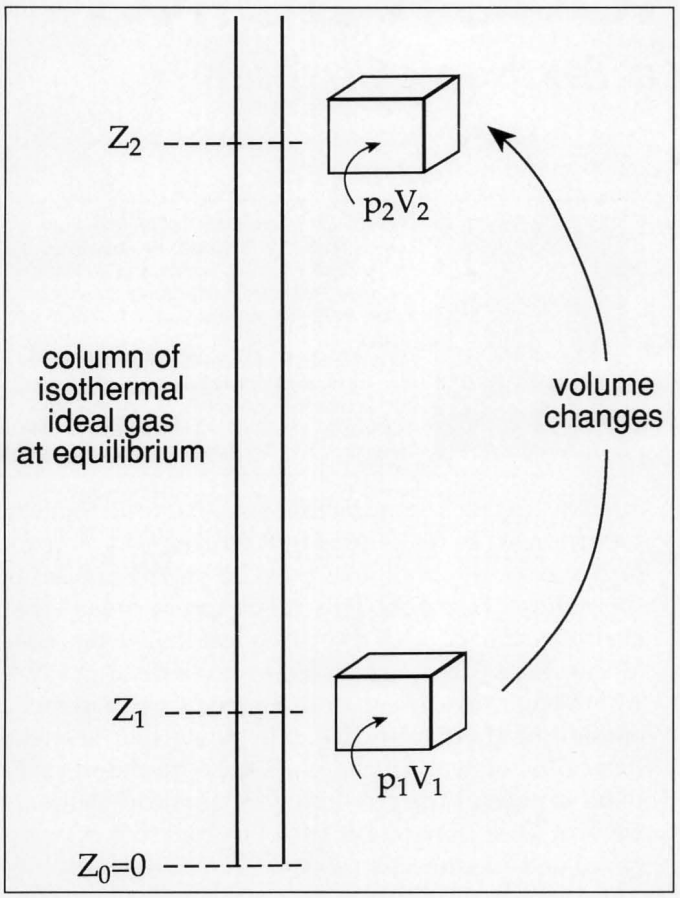
Let us apply this to a column of isothermal ideal gas, such as air, at equilibrium. What happens to the pressure as a chunk of this gas is raised slowly from elevation Z_1 to elevation Z_2? Applying the above general first law expression, noting that $\Delta U = 0$ at constant temperature, we find

$$\cancel{\Delta U} + \Delta E_p + \cancel{\Delta E_k} = \cancel{Q} - \cancel{W}_{shaft} - \int_1^2 p\,dV \qquad (3)$$

Now, for an isothermal ideal gas we can write

$$p = \frac{nRT}{V} \qquad \text{and} \qquad \frac{V_2}{V_1} = \frac{p_1}{p_2}$$

so for a mass m (or n moles) of gas raised from Z_1 to Z_2 we get



$$\frac{mg(Z_2 - Z_1)}{g_c} = -\int_1^2 \frac{nRT}{V}\, dV$$

and, since the molecular mass

$$\overline{mw} = \frac{m}{n}$$

rearranging gives, finally

$$g(Z_2 - Z_1) = \frac{g_c RT}{\overline{mw}} \ell n \frac{p_2}{p_1} \qquad (4)$$

This is an interesting expression. Look at the left-hand side. It is positive, so the right-hand side must also be positive.

This means that $p_2 > p_1$!!

What this says is that as you climb a mountain the air gets thicker, contrary to experience.

What kind of nonsense is this?

Results like this remind me of the story[1] of the great physicist Arnold Sommerfeld, who had written a series of books on various topics in physics. When asked why he hadn't written one on thermodynamics, he is supposed to have said

> *It's a funny subject. The first time you go through it you don't understand it at all. The second time through you think you do except for one or two minor points. The third time you know you don't understand it, but by then you are so used to it, it doesn't bother you.*

At the time he was killed in an accident, the physicist was in the middle of writing a book on ... guess what? Yes—thermodynamics!

To get back to the problem, though—where is the error? Please help me straighten out this curious conclusion.

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The author welcomes comments and solutions to this problem.

A later issue of CEE will list those who have saved thermodynamics from disgrace.

LEARNING THROUGH DOING

A Course on Writing a Textbook Chapter

PHILLIP C. WANKAT
Purdue University
West Lafayette, IN 47907

People learn best when they become *involved* in the process of doing something.[1] While actually working on a project, there is great motivation to learn those things that are needed to finish the project.[2] Properly organized projects which allow students to function as engineers and to receive feedback are an excellent teaching method.

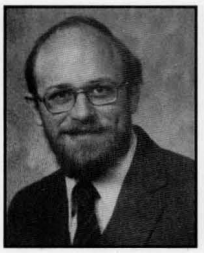
In the course described in this paper, graduate students completed projects which required them to perform one of the functions of a chemical engineering professor—writing an advanced textbook chapter. The idea for a seminar course in this form came from a book by Eble,[3] and the result was a course wherein the students worked harder and learned more than the professor. This is in stark contrast to a "normal" course where the professor works harder and learns more than the students.

THE COURSE

The course was titled "Seminar in Separation Reviews," but the methodology can be used for any technical topic. The prerequisite for the course, an advanced class in ChE separations, ensured that time did not have to be spent teaching basics. Since this was a graduate-level elective, it was not necessary to cover a specific body of material, and the students could pick their own topic. This procedure has the advantage that the students cannot later blame the instructor if their topic proves to be difficult for them.

The seminar was advertised to all students who met the prerequisites, and four students eventually registered. Two other students were interested but could not take the course because of schedule conflicts. A larger class could easily be taught (see "Possible Course Modifications" appearing at the end of this article).

The students were told to produce a professional quality textbook chapter on an advanced topic in separations. To make sure that writing was done for *this* course, the topic could not be on the subject of their thesis research. This requirement meant that everyone started with a very modest knowledge base of the chosen topic. This mimics industrial practice where engineers are often assigned projects in areas outside of their expertise. The topic had to come from a list of over fifty separations, the chapter was to be written at the graduate level, and the students were to work in teams of two. The course grade was based on this project.



Phil Wankat *received his BSChE from Purdue and his PhD from Princeton. He is currently a professor of chemical engineering at Purdue University. He is interested in teaching and counseling, has won several teaching awards at Purdue, and is Head of Freshman Engineering. His research interests are in the area of separation processes, with particular emphasis on cyclic separations, adsorption, preparative chromatography, and simultaneous fermentation and separation.*

During the first class meeting I introduced the course objectives and rules and presented an overview of separations. In the second class, the students analyzed the structure of a separations textbook to determine what is typically included in a textbook chapter. They concluded (with my help) that the following sections are necessary: introduction; body, with appropriate figures and tables; examples, including some for real systems; summary; notation; references; and homework, with a separate solution manual.

In the third class the students critiqued a recent paper from the literature. Fortunately, the paper chosen by the professor had several flaws, and a lively discussion developed—the flaws made it clear that not all papers are created equal. The students were then given a list of journals which included papers on separations, and they were told to skim through several to obtain topic ideas. They came to class with a list of three topics.

We spent much of the fourth class period in teaming up students who had an interest in working

together, and this was eventually accomplished to everyone's satisfaction. The remainder of the period was consumed by a mini-lecture on the different work styles for doing big projects. For example, some engineers prefer to do the work serially by first collecting all the information, then doing calculations, and then writing the report. Others prefer parallel processing and mix their work on the different aspects.

A librarian from the engineering library gave three lectures on manual and computer library search methods. To get started, the teams worked with the librarian on performing computer searches using *Dialog*. The groups were required to do a patent search and to include patents in their bibliographies. Once they had learned how to do computer searches, the students did their searches independently.

We spent much of the remainder of the semester in individual group meetings. I met with each group for twenty-five minutes during the regularly scheduled class meetings, and since each group met with me three times during the week, procrastination was not a problem. On a few occasions the students told me that they had not had time to do any work since the previous meeting, but this never happened twice in a row. I used the group meetings to discuss technical points and work habits.

One work habit that both groups needed assistance with was how to *efficiently* read journal articles. The students had a tendency to try to read all of the papers thoroughly in an effort to completely understand each article. So we had a discussion on how all papers are not of equal importance. I illustrated the concept of *triage* to them—that through skimming, papers can quickly be classified into three piles: important, possibly important, and unimportant. Since only the important papers need to be read carefully, triage can save considerable time.

Later in the semester I used the group meetings to discuss the outlines, the written sections, the examples, and the homework problems. On occasion, when I felt the students were overwhelmed, the group sessions became pep talks. This kind of support facilitates learning.[1,2]

I dispersed other class activities throughout the semester. Once the students had read a reasonable number of articles, I critiqued their notes on the articles. I found that, almost invariably, the students were not keeping complete enough reference citations. Each group presented two informal progress reports to the class during the semester. In addition to serving as informal communication practice, these reports forced the students to integrate their progress and see what else had to be done.

After mid-term break and shortly before the chapter outlines were due, I gave a lecture on organizing papers and writing, following the ideas of Peter Elbow.[4] Briefly stated, Elbow's idea is that writers should do the first draft as quickly as possible, and then rewrite and rewrite. Toward the end of the semester a technical communication expert gave a lecture on common mistakes in written English and a lecture on oral presentations. I gave a mini-lecture on critiqueing papers after the students turned in their first drafts.

In addition to the two informal progress reports, I used a series of partial assignments on the project in an effort to prevent procrastination. A couple of weeks after the mid-term break the teams turned in a detailed outline of their chapters which I quickly returned to them with extensive comments on what could be deleted and what should be added. Then a first draft of the entire chapter (without homework) was turned in and was critiqued by both myself and the other student team—I told the students to read the chapter and to respond as students who were trying to learn the material. The teams then completed a final version of the chapter which corrected the rough draft. The final draft was due on the last class day of the semester, and during finals period each group gave a formal oral presentation.

THE PROFESSOR'S DUTIES

In this class, the professor's duties differ from those in a normal lecture class. The professor must

- *Develop the class schedule and arrange for the guest lecturers*
- *Present three of the eight lectures*
- *Lead the discussion on book chapters, critique the literature article, and critique the first drafts*
- *Develop an extensive list of acceptable topics and set the criteria for acceptable projects*
- *Serve as a facilitator for selection of groups and topics*
- *Read and grade the first drafts and the final chapter plus the solution manual*
- *Listen to and grade the oral reports*
- *Serve as a consultant and listen, question, encourage, and prod during the remaining thirty class periods*
- *(Perhaps the most important) Set the tone that the students could and would produce a professional quality chapter.*

Since little preparation time was needed, during most of the semester I averaged about four hours a week on this course. This number increased, how-

ever, during the two weeks that reports were graded. Overall, the professor's workload in a class of this type is so low as to be almost sinful. Yet, the students learned a lot and the class was very successful! Student learning depends much more on how hard the student works than on how hard the professor works. Since I was able to focus most of my attention on the students instead of on the material, they received much more personal attention than normal. This class was also *fun* to teach. The students all worked hard in a positive and encouraging atmosphere.

The professor's technical knowledge plays a definite role, but it is not as obvious as it is in a lecture class. An experienced professor can quickly tell when the students are getting bogged down on relatively unimportant points; he can look at their chapters and evaluate how a student who did not know the material would react to it; he can see when the students are developing reasonable knowledge structures and including most of the important material; he can understand the text material, the examples, and the homework problems and thus can evaluate them even though he may not have read many of the cited papers. In my opinion, it would be extremely difficult to teach a class like this if the professor is not an expert in the general topic.

THE STUDENT REACTIONS

The students all became very involved in this course. They invested too much time on their projects and had to work to keep the chapters manageable. They thought that learning how to do library searches was extremely useful and expressed the wish that they had learned how to do this sooner. The following quote from Quarderer is appropriate: "Four to six weeks in the lab can save you an hour in the library."[5]

The students also thought that writing was useful, but difficult. The difficulty involved in developing good homework and example problems surprised them. They found that writing a problem requires better understanding than they could get from merely reviewing the literature.

The students chose to write on Reactive Distillation and on Supercritical Fluid Extraction of Solids. The first topic was almost ideal for this course. There are enough references, but not so many as to overwhelm the students. The material is not covered in any depth in existing distillation texts, but is of considerable industrial and academic interest. *Aspen Plus* was used to develop example and homework problems and solutions.

The second topic was much more of a challenge, mainly because of the huge number of references (almost 19,000 were identified in the computer search). This team had more difficulty in limiting their chapter and in finding appropriate data for examples and homework. They eventually decided to focus on coffee decaffeination since it is the most important industrial process and since there is more information available on this process than on others. They also wrote their own computer programs to solve some of the examples and homework problems.

The reports were excellent as student papers and would be acceptable, but not outstanding, as professional contributions. After one semester of studying a topic, the students' knowledge base remained thin. This was evident from their inability to critically evaluate the work they were reporting on and from their difficulty in writing good examples.

Student evaluations showed that half the students agreed, and half strongly agreed, with the statement that this was among the best courses they had ever taken. Three of the students strongly agreed, while one student was undecided, about the statement that this instructor was among the best teachers they had known. Since the professor did not teach in the traditional sense, it is difficult to interpret this result.

In general, the students thought the course was intellectually fulfilling, that it contributed significantly to their professional growth, and it provided a good background for further study. They also put a lot of effort into the class, were satisfied with their accomplishments, and thought they had done well.

POSSIBLE COURSE MODIFICATIONS

By putting the students into groups of three, one professor could handle up to twelve students. Group meetings with the instructor every other class meeting (that is, three times every two weeks) for twenty-five minutes should be sufficient. With three people in the group, students would still receive significant individual attention. The effort required to grade projects would double with four groups, but grading only occurred twice during the semester. The basic format should be retained with this number of students, including the checkpoints used to minimize procrastination.

The students suggested requiring, or strongly encouraging, all new students to take this course during their second semester. At this point in their studies, new students have chosen a thesis project and a major professor, so the textbook chapters could be written on their thesis topics. Because of the

broad range of topics involved, however, one professor could not teach the course without assistance. The professor in charge could serve as a course coordinator and could present the lectures, while other professors would be involved in working with the groups containing their new students. This procedure would structure the process of learning how to do library research, it would give the students a chance to get a good start on understanding the literature in their research area, and it would provide an early opportunity to improve communication skills. During the process of developing their chapters (particularly the examples and the homework) most students will obtain a good picture of what needs to be done in a given area, and the net effect should be a faster start in research.

The difficulties of a team-taught course include ensuring uniformity in the group meetings and in grading. In addition, students who have not had a graduate-level course in the general area of their topic may have extreme difficulty reading the literature. They would either have to delay taking the course or get extra help from their major professor.

COMMENTS

This course was unusual as a graduate course in chemical engineering since the focus was on learning the *processes* of doing library research and writing a book chapter instead of on learning specific knowledge. Since the students found their own sources and charted their own paths, there was very little structure for the technical material. But there was quite a bit of structure and support for the processes of doing library research and in developing a book chapter. This structure (deadlines, lectures, and continual meetings) is probably necessary to prevent procrastination.

Obviously, the students learned technical content in addition to the process. The content learned was in one narrow area, but with significant depth. A normal lecture-homework-test course could probably cover at least twice as much content, but it is doubtful that the students would learn the material as well, and they certainly would not learn how-to-learn as well as they did in this course.

The original course plan was to ask students to write critical reviews. Discussions in the graduate committee convinced me, however, that this was inappropriate since the students did not have enough expertise to critically evaluate papers. So the course plan was changed to have the students write textbook chapters. In addition, the students would have to develop example and homework problems. Developing problems stretched the students and forced them to learn material they might otherwise only half learn. Including problems also forced the students to write computer programs or to use simulation programs. Overall, asking the students to write a textbook chapter is an excellent pedagogical approach.

The students had to work in teams, and this, of course, follows normal industrial practice. In addition, the projects were too big to be done by a single student within a reasonable period of time, so the team members encouraged each other when the task appeared overwhelming (as it did midway through the semester). The members of one team worked very well together. Their chapter meshed well and it was not obvious which student wrote which section. The other team, however, needed significant encouragement to work together. For much of the semester, the group meetings with the professor served as this team's only point of contact. Their chapter showed a seam where the two parts were glued together. Of course, the presence of seams in multi-author textbooks is not unusual.

SUMMARY

In this seminar course, the students became involved in the processes of doing a literature search and in writing a textbook chapter. As a result of learning these processes, in the future they will be able to learn more efficiently on their own. The professor functioned as a consultant rather than a lecturer, and the net result was that most of the effort and learning was done by the students.

ACKNOWLEDGMENT

The assistance of the engineering librarian, Ms. Jean Poland, and the technical communication expert, Dr. Frank Oreovicz, in teaching this course is gratefully acknowledged. Discussions with Professor Nick Delgass were crucial to the course design. The enthusiasm and participation of the students made the course a success.

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THE DU PONT TEACHING FELLOWSHIP PROGRAM

1991 Teaching Experiences

Editorial Note:

The DuPont Teaching Fellows Program was initiated in 1990 to complement the objectives of the DuPont Fellowship Program in chemical, mechanical, and electrical engineering. The Teaching Fellows Program was initiated to encourage high-quality students to obtain PhD degrees and enter academia.

There were six DuPont Teaching Fellowships awarded in chemical engineering in 1991: Linda J. Broadbelt, Gregory S. Fisher, Walter M. Hart, Michael L. Luyben, Steven A. McCluney, and Ronald D. Shaver. DuPont teaching fellows were required to have responsibility for one undergraduate course. The following article describes the teaching experience of five of these students, written by the students themselves.

We thank Professor TW Fraser Russell, who provided the inspiration, advice, and compilation of the material for this presentation.

NAME: ***Steven A. McCluney***

DEPARTMENT: Chemical Engineering UNIVERSITY: Texas A&M University
COURSE TAUGHT: "Chemical Engineering Reactor Design/Kinetics" NUMBER OF STUDENTS: 24
TEXT USED: *Fundamentals of Chemical Reaction Engineering,* by Charles D. Holland and Rayford G. Anthony; Prentice Hall Book Company, Publisher
FACULTY MENTOR: Dr. Rayford Anthony
NUMBER OF YEARS OF GRADUATE EDUCATION COMPLETED: 6
THESIS TOPIC: Modeling AC Impedance Behavior of Coated Electrodes
THESIS ADVISOR: Dr. Ralph White

Teaching an undergraduate course was an extremely valuable and enjoyable experience for me. I feel that in many ways I learned as much as I taught, and I was surprised to find that I still remembered a lot of the material that I had not used for several years. I also discovered that teaching a subject is the best way to become thoroughly familiar with it, both through preparing lessons and through trying to answer students' often in-depth questions. Finally, I learned that teaching involves dedication and patience. In order to teach well, one must be willing to put in the necessary time to carefully prepare a lesson and to try to anticipate any questions which may be raised. One must also be willing to take the time to explain a concept clearly and at the students' level.

I was given almost complete freedom in teaching the course; I discussed my teaching plans with my faculty mentor several times during the semester, but, in general, I was solely responsible for preparing each lecture, and my lectures were not monitored. Since my mentor coauthored the course textbook, I had a clear guideline of the material I was expected to cover. I was also given examples of exams and course notes from previous semesters. On an average, I spent one to two hours preparing each lecture, depending on its content. I also worked each homework assignment so I would be able to explain the concepts as clearly as possible to the students.

In summary, teaching an undergraduate course was a rewarding experience. I now have a greater respect for professors who work hard to be good teachers in addition to researchers. I hope to eventually have a career which will allow me to teach college-level courses—either as a college professor or as a guest instructor from industry. ❐

NAME: ***Ronald D. Shaver***

DEPARTMENT: Chemical Engineering UNIVERSITY: Oklahoma State University
COURSE TAUGHT: "Introduction to Chemical Process Engineering" NUMBER OF STUDENTS: 24
TEXT USED: *Elementary Principles of Chemical Processes,* 2nd ed.;
by Richard M. Felder and Ronald W. Rousseau; John Wiley & Sons, Inc., Publisher
FACULTY MENTOR: Dr. Ruth Erbar
NUMBER OF YEARS OF GRADUATE EDUCATION COMPLETED: 3.5
THESIS TOPIC: Equation of State Development for Equilibrium Predictions
THESIS ADVISOR: Dr. K.A.M. Gasem

Having the opportunity to serve as a 1991-92 DuPont Teaching Fellow gave me some valuable insights into teaching at the college level. The course I taught was the sophomore-level "Introduction to Chemical Process Engineering."

Traditionally, chemical engineering attracts only the best students, and this course represents the first challenging course that most of them take. This teaching experience taught me how to properly organize a fast-paced engineering course and how to recognize when students properly understand the necessary concepts, as well as when they do not.

Daily preparation for the course required much more time than I had originally thought it would. I found that not only must the lectures be presented in an organized, logical manner, but also that every possible question that may be asked by someone being exposed to the material for the first time must be anticipated.

Throughout the semester I had the privilege of being able to consult the late Dr. Ruth Erbar about details of course organization and how to structure some special projects to ensure that the students obtained the maximum benefit and preparation for later courses. We often talked about the students' reactions to various situations; for example, we both felt that in order for students to best learn the covered topics, they should be pushed to the limit of their abilities. Although many students were initially intimidated by exams that challenged even the best students in the class, several of them commented at the end of the course that the material they best understood was the material they initially had the most trouble comprehending.

Throughout the course I maintained an open-door policy and encouraged the students to come discuss any problems they might be having with the course material. There is a wonderful satisfaction in seeing students' eyes light up when they first truly understand a concept that they've been struggling with, and even more joy in seeing students become excited about a topic and excelling beyond that which is required or expected of them.

Being a DuPont Teaching Fellow was a wonderful experience, and I fully intend to pursue university teaching at some future point in my career. ❐

NAME: ***Greg Fisher***

DEPARTMENT: Chemical Engineering UNIVERSITY: Michigan State University
COURSE TAUGHT:" Material and Energy Balances" NUMBER OF STUDENTS: 52
TEXT USED: *Elementary Principles of Chemical Processes,* 2nd edition; by Richard M. Felder
and Ronald W. Rousseau; John Wiley & Sons, Inc., Publisher
FACULTY MENTOR: Dr. Alec Scranton
NUMBER OF YEARS OF GRADUATE EDUCATION COMPLETED: 5
THESIS TOPIC: The Effect of Interphase Composition on Adhesion in Polyphenylene Sulfide/Carbon Fiber Composites
THESIS ADVISOR: Dr. Lawrence T. Drzal

The time I spent as a DuPont Teaching Fellow was time well spent. The experience was overwhelmingly positive, both as an introduction to college-level lecturing and in organizing familiar material into a package that beginners could understand.

I actually received instruction from my faculty mentor the term before I taught the course when I served as his teaching assistant. This enabled me to be completely on my own during the time I taught the course, heightening the experience even more for me. Teaching the course required approximately ten to fifteen hours a week. The help of a teaching assistant and two homework graders allowed me to concentrate on writing and giving lectures, on writ-

ing exams, and on assigning grades.

It was disappointing to discover that some students expected a 3.0/4.0 grade "just for showing up," and that often the students who needed extra help the most were the very ones to request it too late. On the other hand, I was delighted to find that many students were eager to learn the material, that some of the students who struggled in the beginning worked hard and did well in the end, and that establishing a good rapport with most of the students was relatively easy.

The most difficult part of teaching the course was designing a fair grading scale, and keeping as many of the students as possible involved in lectures provided another challenge. Working with the students to help them learn was the most rewarding aspect of teaching the course.

I enjoyed the teaching experience a great deal and would like to pursue a career in teaching after gaining some industrial experience. Since chemical engineering is such an applied field, I believe students appreciate instructors who have actually worked in industry.

I believe the DuPont Teaching Fellows program is a worthwhile program and truly appreciate the opportunity I had to participate in it. ❐

NAME: ***Michael Luyben***

DEPARTMENT: Chemical Engineering UNIVERSITY: Princeton University
COURSE TAUGHT: "Introduction to Chemical Engineering" NUMBER OF STUDENTS: 45
TEXT USED: *Elementary Principles of Chemical Processes,* 2nd ed., by Richard M. Felder and Ronald W. Rousseau; John Wiley & Sons, Inc., Publisher
FACULTY MENTOR: Dr. S. Sundaresan
NUMBER OF YEARS OF GRADUATE EDUCATION COMPLETED: 4
THESIS TOPIC: A Multi-Objective Optimization Approach for Analyzing the Interaction of Design and Control
THESIS ADVISOR: Dr. C.A. Floudas

My service as a DuPont Teaching Fellow in 1991 at Princeton University provided a valuable opportunity for me to learn about teaching. The course I taught, "Introduction to Chemical Engineering," contained material with some approaches, terminology, and jargon which were unfamiliar to the first- and second-year undergraduates, and it was important to remember and consider this when I was planning classes and answering questions.

The course challenged me to communicate ideas as clearly and enthusiastically as possible, since success in this respect usually engaged the students' intellectual curiosity and challenged them to think clearly and independently. Teaching involves not so much an imparting of information as it does training students' minds to think critically and teaching them to approach problems both systematically and creatively. Such a goal demands a lot of practical experience, and this opportunity to teach gave me that experience.

The course culminated in a case-study project which required the students to work in groups and to tie together all of the material they had learned in the course. This gave them a better perspective on the type of analysis used in chemical engineering and demanded more sophistication in applying general principles to a problem that was larger than the weekly homework assignments to which they were accustomed. The students seemed to think this was a helpful survey of the course material and it proved to be a valuable educational tool.

I cannot make generalizations about how students learn since each of them is an individual. Some of them understand the subject quickly just by reading the book, while some learn from doing the homework assignments and still others have to come by the office and ask questions to clarify the material. The real teaching challenge lies in finding an appropriate balance of difficulty in the course material. Many students have a lot of pressure on them with their coursework load, and it compounds the problem when universities place so much emphasis on research rather than on teaching. The DuPont Teaching Fellows Program contributes significantly to support teaching ability and works to counteract this trend.

The course required three to four hours a week of lecture preparation; I also spent quite a bit of additional time with the individual students, answering questions. The faculty mentor for the course occasionally attended class while I taught, and at least once a week we discussed teaching, course material, and overall plans.

I would like to again thank DuPont for providing this opportunity for me to gain undergraduate teaching experience. I found that I greatly enjoy teaching

and want to pursue it as a career. I feel it will be a challenging and rewarding occupation. DuPont has generously provided the support and encouragement for me and for other graduate students in chemical engineering to consider careers in teaching through their Teaching Fellows Program. ❐

NAME: ***Linda J. Broadbelt***

DEPARTMENT: Chemical Engineering UNIVERSITY: University of Delaware
COURSE TAUGHT: "Chemical Engineering Kinetics" NUMBER OF STUDENTS: 20
TEXT USED: *Chemical Reaction Engineering,* 2nd ed., by Octave Levenspiel; John Wiley & Sons, Publisher
FACULTY MENTOR: Dr. TW Fraser Russell
NUMBER OF YEARS OF GRADUATE EDUCATION COMPLETED: 3
THESIS TOPIC: Thermal Degradation of High Performance Polymers and Integration of Structure, Reactivity, and Property
THESIS ADVISOR: Dr. Michael T. Klein

The experience I had as a DuPont Teaching Fellow was extremely positive and reinforced my desire to pursue a teaching career. It also forced me to increase my knowledge of reaction engineering and kinetics. Most importantly, it revealed to me that it is quite different to be up in front of the class teaching a course than it is to sit at a desk and listen!

Teaching style is directly related to an individual's personality. I found I was most comfortable when I did not try to adopt someone else's style and just acted naturally. I learned a great deal, however, from watching and listening to Drs. Russell and Orbey when they taught.

I found that in-class problem sessions were invaluable. The problems generated excellent class discussion and dramatically reinforced learning while at the same time providing ample opportunity for student-teacher interaction. It also prevented a monotonous, long-winded monologue at the blackboard.

I had the benefit of sitting in Dr. Orbey's lecture in advance of mine. The course was taught in two 20-student sections. This allowed me to improve my own grasp of the material, and more importantly, to assess the students' responses to the various facets of the lecture. Dr. Russell sat in on most of my lectures and gave me excellent feedback about my style and the students' reactions. He was also an invaluable resource during a lecture, providing knowledge and insight from his years of experience. Having such an active and interested mentor was the most crucial element in making my teaching experience so rewarding and successful.

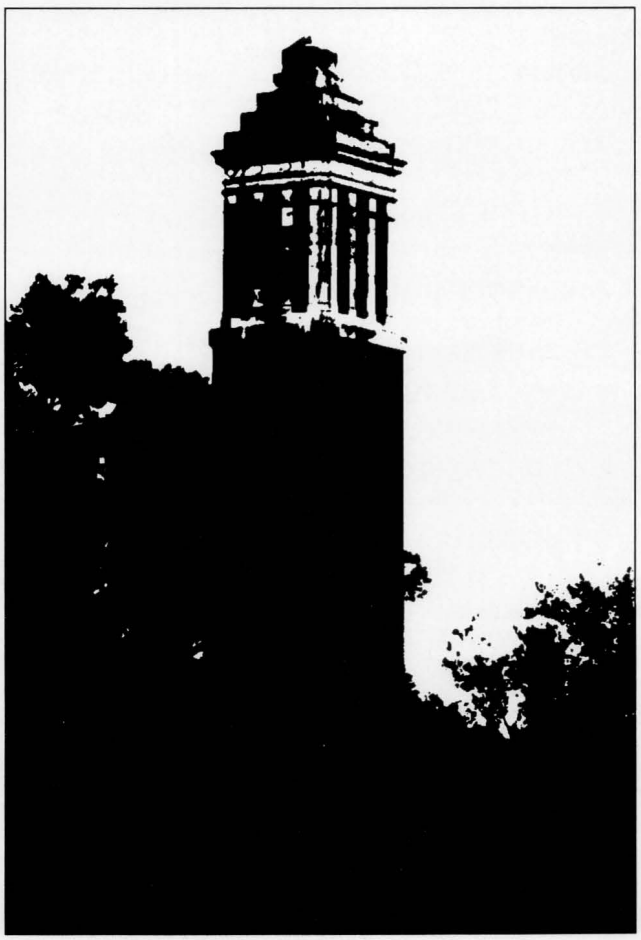
I also received invaluable feedback from the students. It was not hard to determine when a certain approach was successful—the students were not afraid to participate in discussions or to voice their frustrations when they had them. They enjoyed the in-class problems and felt they were beneficial to learning the material. They also voiced appreciation of any extra effort I expended, such as long office hours, help sessions, etc., and took advantage of any help I offered. I found that one of the most important elements of establishing good rapport with the students was knowing and calling them by name.

A more negative facet was that teaching reminded me what it was like to be an undergraduate student, when the end goal was not necessarily the learning or the acquired knowledge, but the grade received. Students frustratingly begged for additional points, asked for extensions on their homework, complained about unfair or difficult exams, or lamented the poor choice of a textbook. I had to remind myself that only hard work earns a high grade and that learning is always the ultimate goal. I found assigning grades at the end of the course to be the most difficult part of teaching. It was hard not to let an element of subjectivity to creep into the grade of a student with whom I had significant personal interaction. While there is room in the grading system for effort expended and class participation to be considered along with reliance on numerical analysis of exams and homework, I tried not to let personal feelings cloud my judgment.

The time commitment involved was immense and involved preparing lectures, exams, and interesting homework in addition to student-teacher interaction outside of class. I had the benefit of two excellent mentors who made all the tasks much easier and less time consuming. I estimate that we spent two or three hours a week discussing lecture preparation, class material, exam preparation and grading, and teaching style.

I feel very fortunate to have been a part of the DuPont Teaching Fellows program. My mentors were exceptional and contributed greatly to making the experience so rewarding. ❐

CHEMICAL ENGINEERING PROGRAMS AT THE UNIVERSITY OF ALABAMA



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

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

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

FACULTY

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

RESEARCH INTERESTS

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THE UNIVERSITY OF ARIZONA

TUCSON, AZ

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

THE FACULTY AND THEIR RESEARCH INTERESTS

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Microbiological Hazardous Waste Treatment, Metals Speciation and Toxicity

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

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Protein Separation, Electrophoresis, Membrane Transport

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

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

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

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

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

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

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

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Aerosols, Hazardous Waste Incineration, Microcontamination

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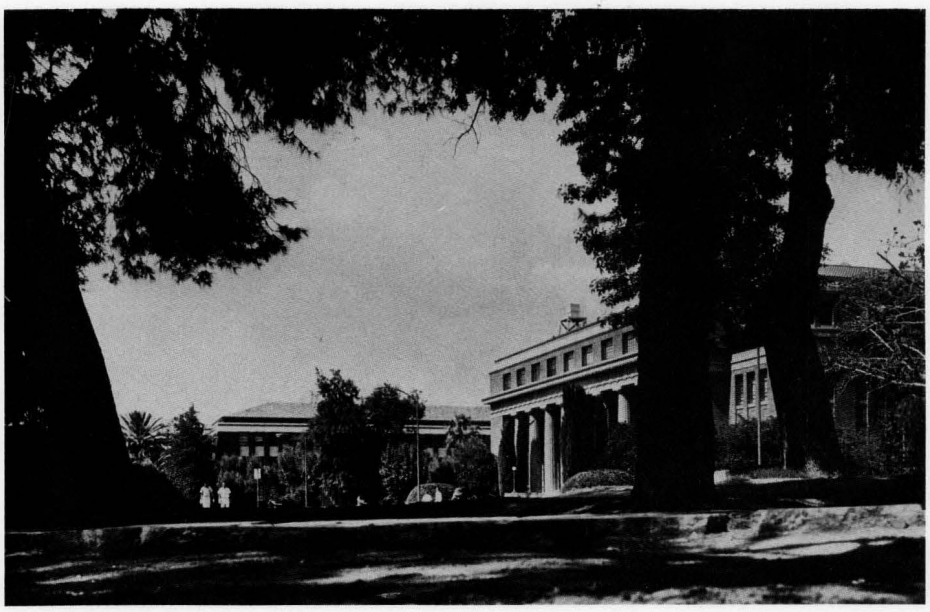

For further information, write to

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

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Women and minorities are encouraged to apply.

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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

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

Bioengineering

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

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

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

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

Materials Science & Engineering

Alford, Terry L., Ph.D., Cornell U. • Electronic Materials • Physical Metallurgy • Electronic Thin Films • Surface/Thin Film

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

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

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

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

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

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

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

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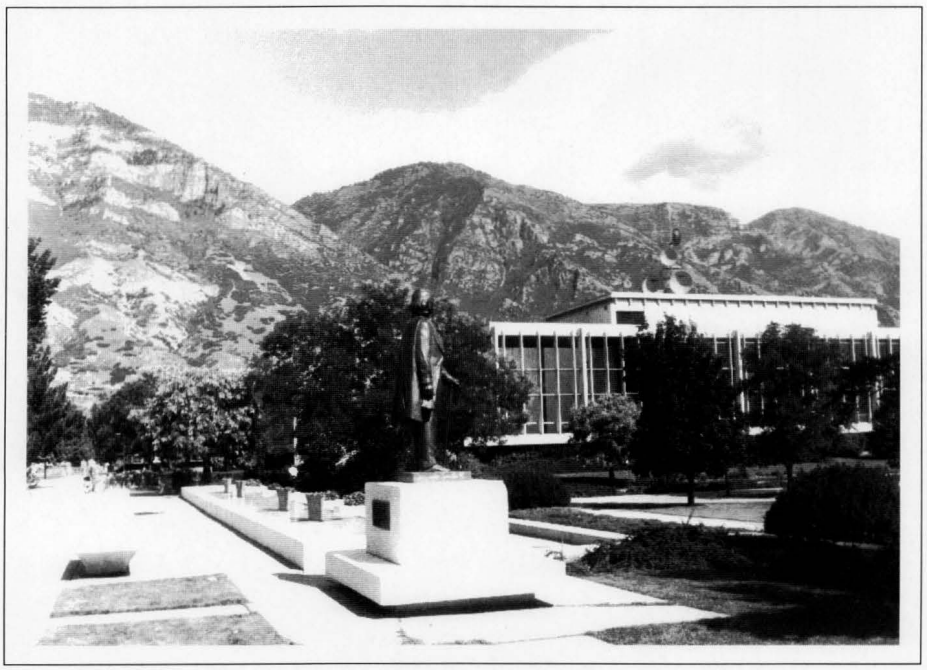

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Graduate Coordinator
Department of Chemical Engineering, 350 CB
Brigham Young University
Provo, Utah 84602

Tel: (801) 378-2586

THE UNIVERSITY OF CALGARY

DEPARTMENT OF CHEMICAL AND PETROLEUM ENGINEERING

The Department offers graduate programs leading to the M.Sc. and Ph.D. degrees in Chemical Engineering (full-time) and the M.Eng. degree in Chemical Engineering or Petroleum Reservoir Engineering (part-time) in the following areas:

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- **Biomedical Engineering**
- **Environmental Engineering**
- **Modeling, Simulation & Control**
- **Petroleum Recovery & Reservoir Engineering**
- **Process Development**
- **Reaction Engineering/Kinetics**
- **Thermodynamics**
- **Transport Phenomena**

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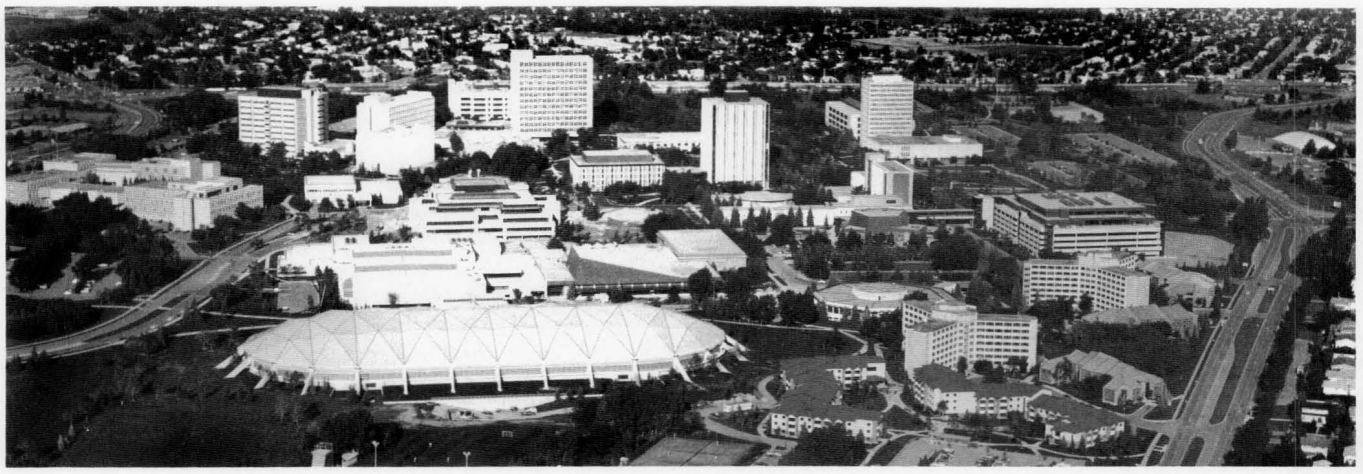
Dr. A. K. Mehrotra • Chair, Graduate Studies Committee
Department of Chemical and Petroleum Engineering
The University of Calgary • Calgary, Alberta, Canada T2N 1N4



The University is located in the City of Calgary, the Oil capital of Canada, the home of the world famous Calgary Stampede and the 1988 Winter Olympics. The City combines the traditions of the Old West with the sophistication of a modern urban center. Beautiful Banff National Park is 110 km west of the City and the ski resorts of Banff, Lake Louise,and Kananaskis areas are readily accessible. In the above photo the University Campus is shown with the Olympic Oval and the student residences in the foreground. The Engineering complex is on the left of the picture.

THE UNIVERSITY OF CALIFORNIA AT BERKELEY . . .

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

RESEARCH INTERESTS

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ENERGY UTILIZATION
FLUID MECHANICS
KINETICS AND CATALYSIS
POLYMER SCIENCE AND TECHNOLOGY
PROCESS DESIGN AND DEVELOPMENT
SEPARATION PROCESSES
SURFACE AND COLLOID SCIENCE
THERMODYNAMICS

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- **Environmental Chemistry**
- **Environmental Engineering**
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- **Materials Processing**
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- **Microstructure of Materials**
- **Optimization**
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- **Separation Processes**
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Biochemical Engineering Program
School of Engineering
University of California
Irvine, CA 92717-2575

CHEMICAL ENGINEERING AT

UCLA

RESEARCH AREAS

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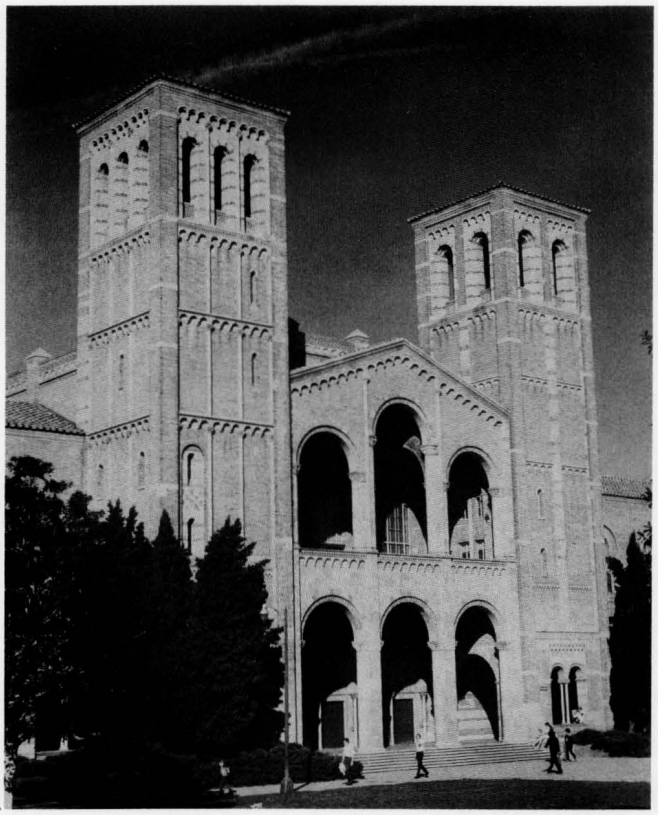
- Process Design, Dynamics, and Control
- Polymer Processing and Transport Phenomena
- Kinetics, Combustion, and Catalysis
- Surface and Interface Engineering
- Electrochemistry and Corrosion
- Biochemical Engineering
- Aerosol Science and Technology
- Air Pollution Control and Environmental Engineering



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Y. Cohen

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S. K. Friedlander

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V. Manousiouthakis

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K. Nobe

L. B. Robinson
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A. R. Wazzan

PROGRAMS

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

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

CONTACT

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

UNIVERSITY OF CALIFORNIA
SANTA BARBARA

• FACULTY AND RESEARCH INTERESTS •

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ERAY S. AYDIL Ph.D. *(University of Houston)* • Microelectronics Materials Processing
SANJOY BANERJEE Ph.D. *(Waterloo)* • Two-Phase Flow, Chemical & Nuclear Safety, Computational Fluid Dynamics, Turbulence.
BRADLEY F. CHMELKA Ph.D. *(U.C. Berkeley)* • Guest/Host Interactions in Molecular Sieves, Dispersal of Metals in Oxide Catalysts, Molecular Structure and Dynamics in Polymeric Solids, Properties of Partially Ordered Materials, Solid-State NMR Spectroscopy.
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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)** • Mechanics of Materials, Radiation Damage.
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ERIC McFARLAND Ph.D. *(M.I.T.)* M.D. *(Harvard)* • Biomedical Engineering, NMR and Neutron Imaging, Transport Phenomena in Complex Liquids, Radiation Interactions.
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T. G. THEOFANOUS Ph.D. *(Minnesota)* • Nuclear and Chemical Plant Safety, Multiphase Flow, Thermalhydraulics.
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JOSEPH A. N. ZASADZINSKI Ph.D. *(Minnesota)* • Surface and Interfacial Phenomen, Structure of Microemulsions.

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

THE UNIVERSITY

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

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

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Nicholas W. Tschoegl (Emeritus)
Zhen-Gang Wang

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

For further information, write

Professor Mark E. Davis
Chemical Engineering 210-41 • California Institute of Technology • Pasadena, California 91125

Clues

John L. Anderson
Membrane and colloid transport phenomena

Lorenz T. Biegler
Process simulation and optimization

Paul A. DiMilla
Cellular and biomolecular engineering; cell membranes

Michael M. Domach
Biochemical engineering and cell biology

Ignacio E. Grossmann
Batch process synthesis and design

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

Annette M. Jacobson
Solubilization and surfacant adsorption phenomena

Myung S. Jhon
Magnetic and magneto-optical recording

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

Gary J. Powers
Decision-making in the design of chemical processing systems

Dennis C. Prieve
Transport phenomena and colloids, especially electrokinetic phenomena

Jennifer L. Sinclair
Multiphase flow

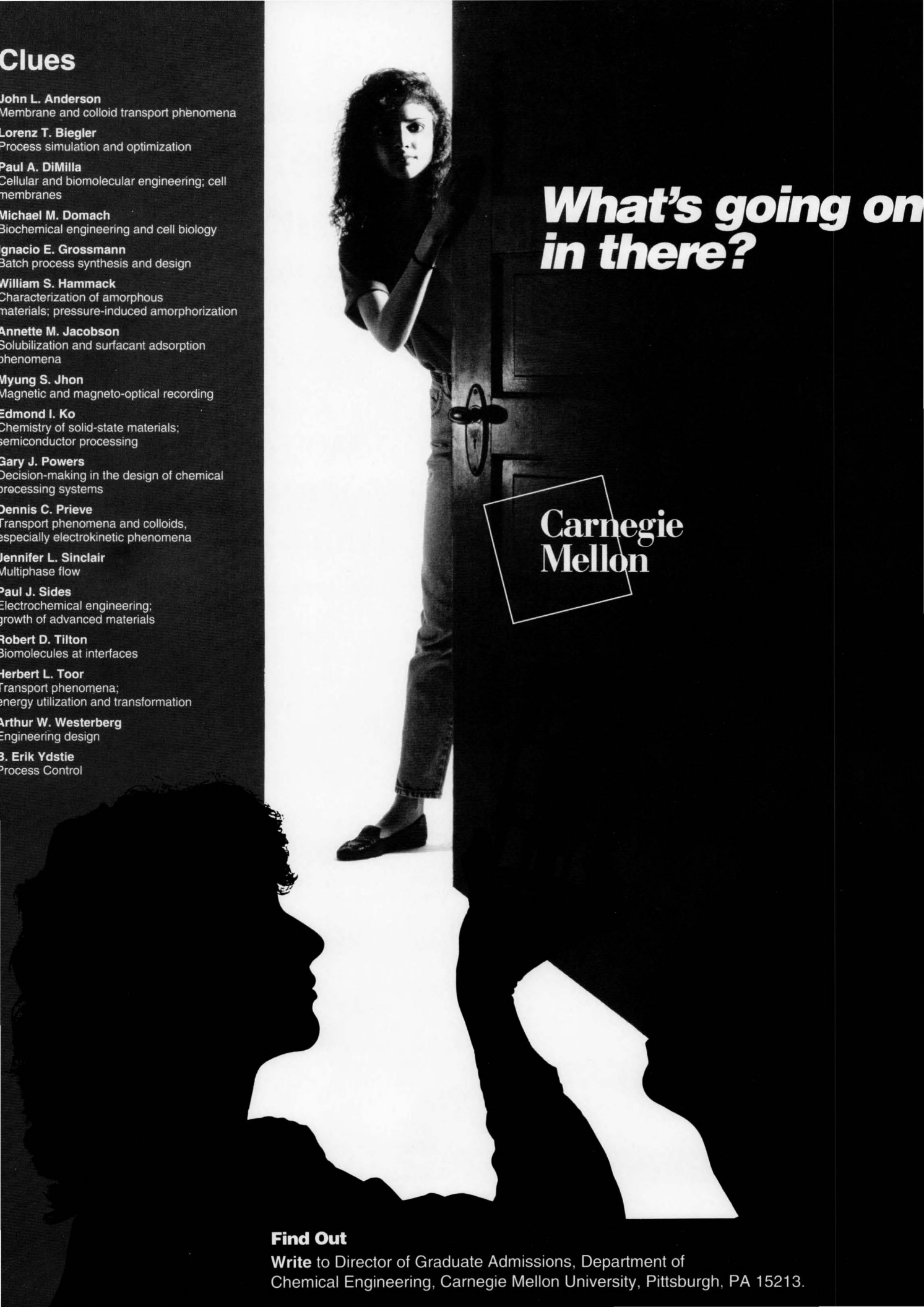
Paul J. Sides
Electrochemical engineering; growth of advanced materials

Robert D. Tilton
Biomolecules at interfaces

Herbert L. Toor
Transport phenomena; energy utilization and transformation

Arthur W. Westerberg
Engineering design

B. Erik Ydstie
Process Control



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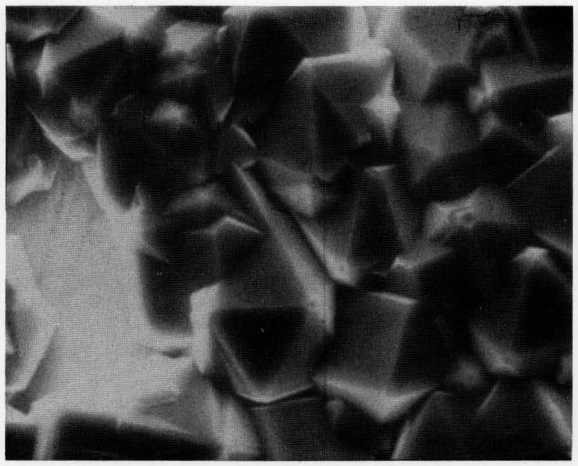

Diamond crystals synthesized by graduate student C. Kovach.

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

Faculty and Specializations

John C. Angus, Ph.D. 1960, University of Michigan
Diamond and diamond-like films, redox equilibria

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

Philip W. Morrison, Jr., Ph.D. 1987, University of California (Berkeley)
Materials synthesis, semiconductor processing, in-situ diagnostics

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

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

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Faculty

Amy Ciric	**Robert Jenkins**
Joel Fried	**Yuen-Koh Kao**
Stevin Gehrke	**Soon-Jai Khang**
Rakesh Govind	**Jerry Lin**
David Greenberg	**Glenn Lipscomb**
Daniel Hershey	**Neville Pinto**
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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.

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Director, Graduate Studies
Department of Chemical Engineering, # 0171
University of Cincinnati
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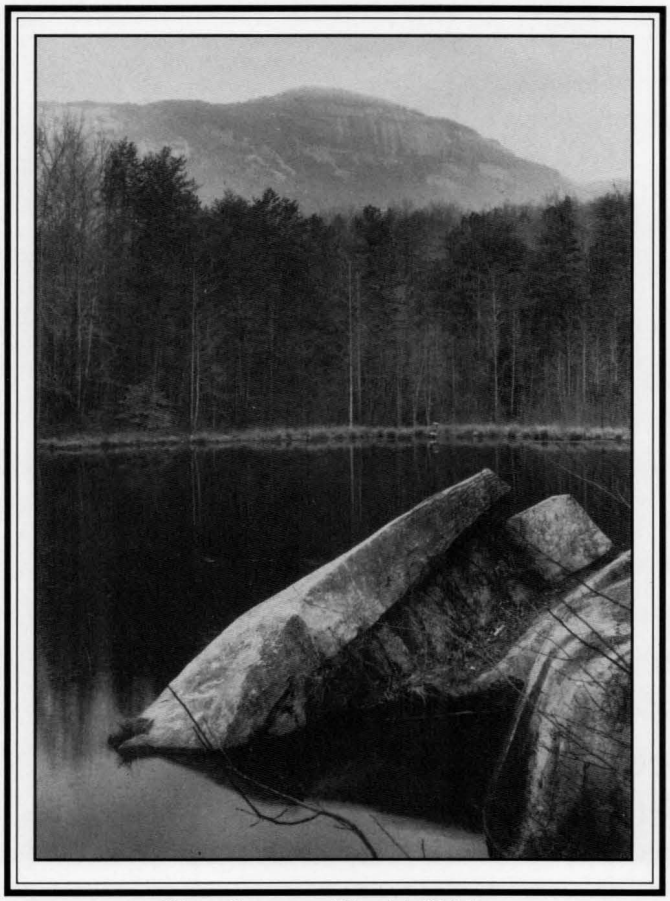

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The Faculty

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John N. Beard	Douglas E. Hirt	Richard W. Rice
Dan D. Edie	Stephen S. Melsheimer	Mark C. Thies
Charles H. Gooding	Joseph C. Mullins	

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Clemson University • Clemson, South Carolina 29634-0909 • (803) 656-3055

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BOULDER

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FACULTY

CHRISTOPHER N. BOWMAN • *Assistant Professor*
Ph.D., Purdue University, 1991

DAVID E. CLOUGH • *Professor*
Ph.D., University of Colorado, 1975

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

JOHN L. FALCONER • *James and Catherine Patten Professor*
Ph.D., Stanford University, 1974

YURIS O. FUENTES • *Assistant Professor*
Ph.D., University of Wisconsin-Madison, 1990

R. IGOR GAMOW • *Associate Professor*
Ph.D., University of Colorado, 1967

HOWARD J. M. HANLEY • *Professor Adjoint*
Ph.D., University of London, 1963

DHINAKAR S. KOMPALA • *Associate Professor*
Ph.D., Purdue University, 1984

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

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

W. FRED RAMIREZ • *Professor*
Ph.D., Tulane University, 1965

THEODORE W. RANDOLPH • *Associate Professor*
Ph.D., University of California, Berkeley, 1987

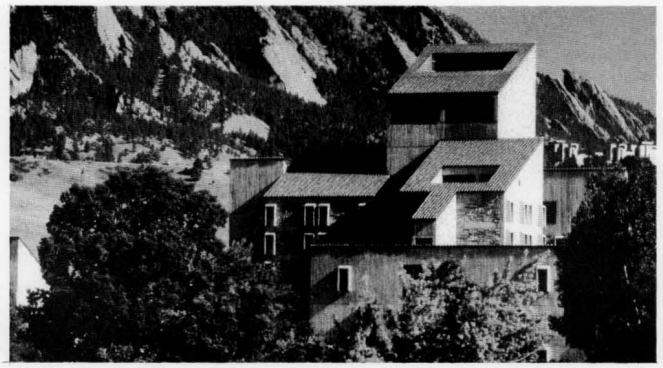
ROBERT L. SANI • *Professor*
Director of Center for Low-gravity Fluid Mechanics and Transport Phenomena
Ph.D., University of Minnesota, 1963

EDITH M. SEVICK • *Assistant Professor*
Ph.D., University of Massachusetts, 1989

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

PAUL W. TODD • *Research Professor*
Ph.D., University of California, Berkeley, 1964

RONALD E. WEST • *Professor*
Ph.D., University of Michigan, 1958



RESEARCH INTERESTS

Biotechnology and Bioengineering
- Bioreactor Design and Optimization
- Mammalian Cell Cultures
- Protein Folding and Purification

Chemical Environmental Engineering
- Global Change
- Pollution Remediation

Materials Science and Engineering
- Catalysis and Surface Science
- Colloidal Phenomena
- Polymerization Reaction Engineering

Membrane Science
- Chemically Specific Separations
- Membrane Transport and Separations
- Polymeric Membrane Morphology

Modeling and Control
- Expert Systems
- Process Control and Identification

Thermodynamics
- Cryogenics
- Statistical Mechanics
- Supercritical Fluids

Transport Phenomena
- Fluid Dunamics and Suspension Mechanics
- Materials Processing in Low-G

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University of Colorado, Boulder • Boulder, Colorado 80309-0424
•FAX (303) 492-4341

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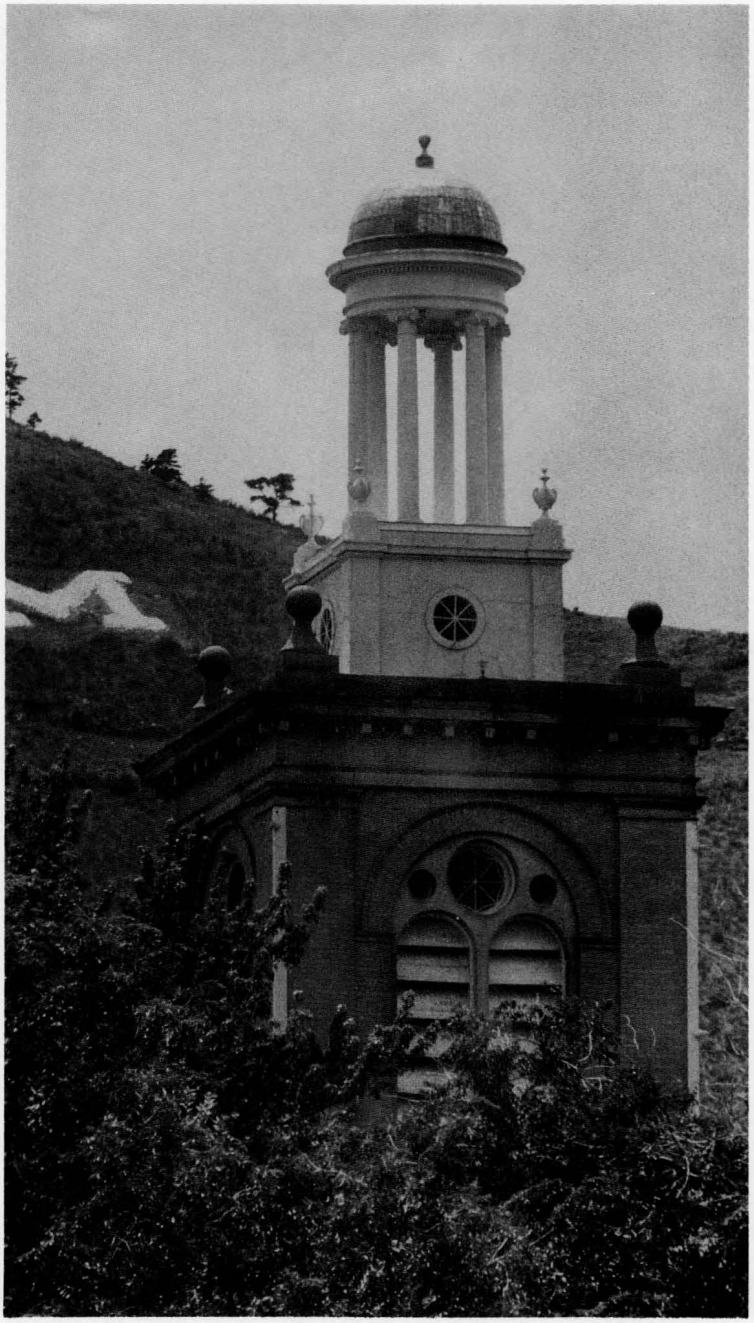

THE FACULTY AND THEIR RESEARCH

R. M. BALDWIN, Professor and Head; Ph.D., Colorado School of Mines. *Mechanisms and kinetics of coal liquefaction, catalysis, oil shale processing, fuels science.*

A. L. BUNGE, Professor; Ph.D., University of California, Berkeley. *Membrane transport and separations, mass transfer in porous media, ion exchange and adsorption chromatography, in place remediation of contaminated soils, percutaneous absorption.*

J.R. DORGAN, Assistant Professor; Ph.D., University of California, Berkeley. *Polymer science and engineering.*

J. F. ELY, Professor; Ph.D., Indiana University. *Molecular thermodynamics and transport properties of fluids.*

J. H. GARY, Professor Emeritus; Ph.D., University of Florida. *Petroleum refinery processing operations, heavy oil processing, thermal cracking, visbreaking and solvent extraction.*

J.O. GOLDEN, Professor; Ph.D., Iowa State University. *Hazardous waste processing, polymers, fluidization engineering*

M.S. GRABOSKI, Research Professor; Ph.D., Pennsylvania State University. *Fuels Synthesis and evaluation, engine technology, alternate fuels*

A. J. KIDNAY, Professor and Graduate Dean; D.Sc., Colorado School of Mines. *Thermodynamic properties of gases and liquids, vapor-liquid equilibria, cryogenic engineering.*

J.T. McKINNON, Assistant Professor; Ph.D., Massachusetts Institute of Technology. *High temperature gas phase chemical kinetics, combustion, hazardous waste destruction.*

R. L. MILLER, Associate Professor; Ph.D., Colorado School of Mines. *Liquefaction co-processing of coal and heavy oil, low severity coal liquefaction, particulate removal with venturi scrubbers, interdisciplinary educational methods*

M. S. SELIM, Professor; Ph.D., Iowa State University. *Heat and mass transfer with a moving boundary, sedimentation and diffusion of colloidal suspensions, heat effects in gas absorption with chemical reaction, entrance region flow and heat transfer, gas hydrate dissociation modeling.*

E. D. SLOAN, JR., Professor; Ph.D. Clemson University. *Phase equilibrium measurements of natural gas fluids and hydrates, thermal conductivity of coal derived fluids, adsorption equilibria, education methods research.*

J. D. WAY, Research Professor; Ph.D. University of Colorado. *Novel separation processes, membrane science and technology, membrane reactors, ceramic and metal membranes, biopolymer adsorbents for adsorption of heavy metals.*

V. F. YESAVAGE, Professor; Ph.D., University of Michigan. *Vapor liquid equilibrium and enthalpy of polar associating fluids, equations of state for highly non-ideal systems, flow calorimetry.*

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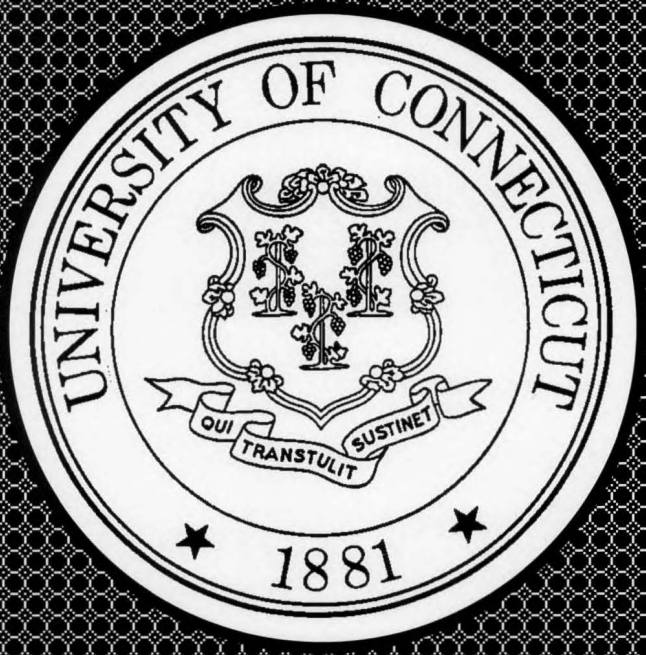
Colorado School of Mines



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FACULTY RESEARCH AREAS

Luke E.K. Achenie, Ph.D., Carnegie Mellon University
Modeling and Optimization, Neural Networks, Process Control

Thomas F. Anderson, Ph.D., University of California, Berkeley
Modeling of Separation Processes, Fluid-Phase Equilibria

James P. Bell, Sc.D., Massachusetts Institute of Technology
Structure-Property Relations in Polymers and Composites, Adhesion

Carroll O. Bennett, Professor Emeritus, Ph.D., Yale University
Catalysis, Chemical Reaction Engineering

Douglas J. Cooper, Ph.D., University of Colorado
Process Control, Neural Networks, Fluidization Technology

Robert W. Coughlin, Ph.D., Cornell University
Biotechnology, Biochemical and Environmental Engineering, Catalysis, Kinetics, Separations, Surface Science

Michael B. Cutlip, Ph.D., University of Colorado
Kinetics and Catalysis, Electrochemical Reaction Engineering, Numerical Meth

Anthony T. DiBenedetto, Ph.D., University of Wisconsin
Composite Materials, Mechanical Properties of Polymers

James M. Fenton, Ph.D., University of Illinois, Urbana-Champaign
Electrochemical and Environmental Engineering, Mass Transfer Processes, Electronic Materials, Energy Systems

Suzanne (Schadel) Fenton, Ph.D., University of Illinois
Computational Fluid Dynamics, Turbulence, Two-Phase Flow

Robert J. Fisher, Ph.D., University of Delaware
Biochemical Engineering and Environmental Biotechnology

G. Michael Howard, Ph.D., University of Connecticut
Process Systems Analysis and Modeling, Process Safety, Engineering Educatio

Herbert E. Klei, Professor Emeritus, Ph.D., University of Connecticut
Biochemical Engineering, Environmental Engineering

Jeffrey T. Koberstein, Ph.D., University of Massachusetts
Polymer Blends/Compatibilization, Polymer Morphology, Polymer Surface and Interfaces

Harold R. Kunz, Ph.D., Rensselaer Polytechnic Institute
Fuel Cells, Electrochemical Energy Systems

Montgomery T. Shaw, Ph.D., Princeton University
Polymer Rheology and Processing, Polymer-solution Thermodynamics

Richard M. Stephenson, Professor Emeritus, Ph.D., Cornell University
Mutual Solubility Measurements, Liquid-Liquid Equilibrium

Donald W. Sundstrom, Professor Emeritus, Ph.D. University of Michigan
Environmental Engineering, Hazardous Wastes, Biochemical Engineering

Robert A. Weiss, Ph.D., University of Massachusetts
Polymer Structure-Property Relationships, Ion-Containing and Liquid Crystal Polymers, Polymer Blends

FOR MORE INFORMATION

Graduate Admissions, 191 Auditorium Road
University of Connecticut, Storrs, CT 06269-3222
Tel. (203) 486-4020

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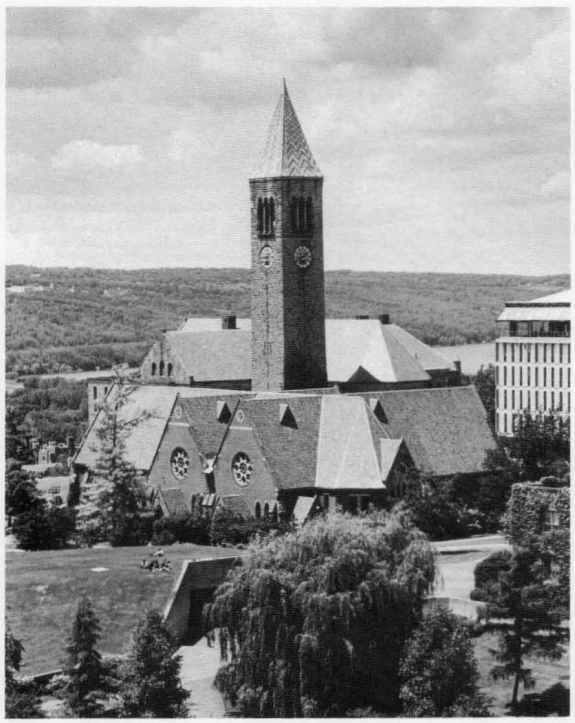

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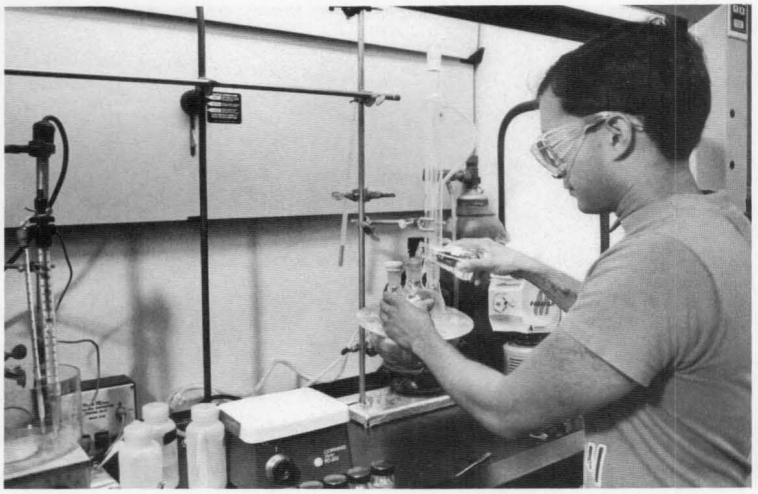

Distinguished Faculty . . .

A. Brad Anton
Paulette Clancy
Claude Cohen
T. Michael Duncan
James R. Engstrom
Keith E. Gubbins
Daniel A. Hammer
Peter Harriott
Donald L. Koch
Robert P. Merrill
William L. Olbricht
A. Panagiotopoulos
Ferdinand Rodriguez
Michael L. Shuler
Paul H. Steen
William B. Streett
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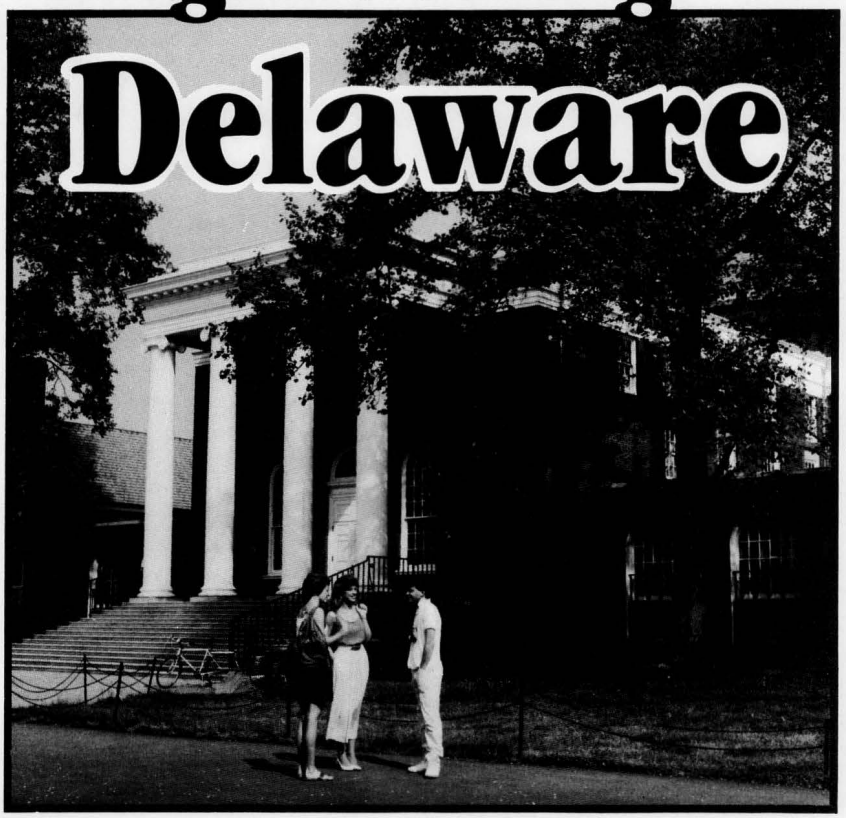
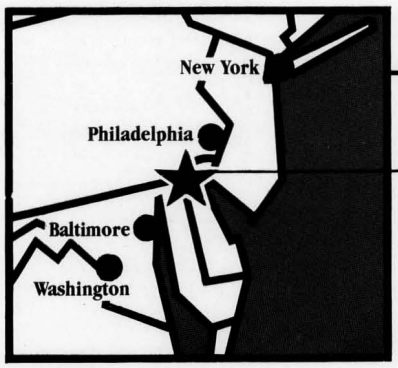


The Faculty

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

The University of Delaware offers M.ChE and Ph.D. degrees in Chemical Engineering. Both degrees involve research and course work in engineering and related sciences. The Delaware tradition is one of strong interdisciplinary research on both fundamental and applied problems. Current fields include **Thermodynamics, Separation Processes, Polymer Science and Engineering, Fluid Mechanics and Rheology, Transport Phenomena, Materials Science and Metallurgy, Catalysis and Surface Science, Reaction Kinetics, Reactor Engineering, Process Control, Semiconductor and Photovoltaic Processing, Biomedical Engineering, Biochemical Engineering, and Colloid and Surfactant Science.**



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Department of Chemical Engineering
University of Delaware
Newark, Delaware 19716

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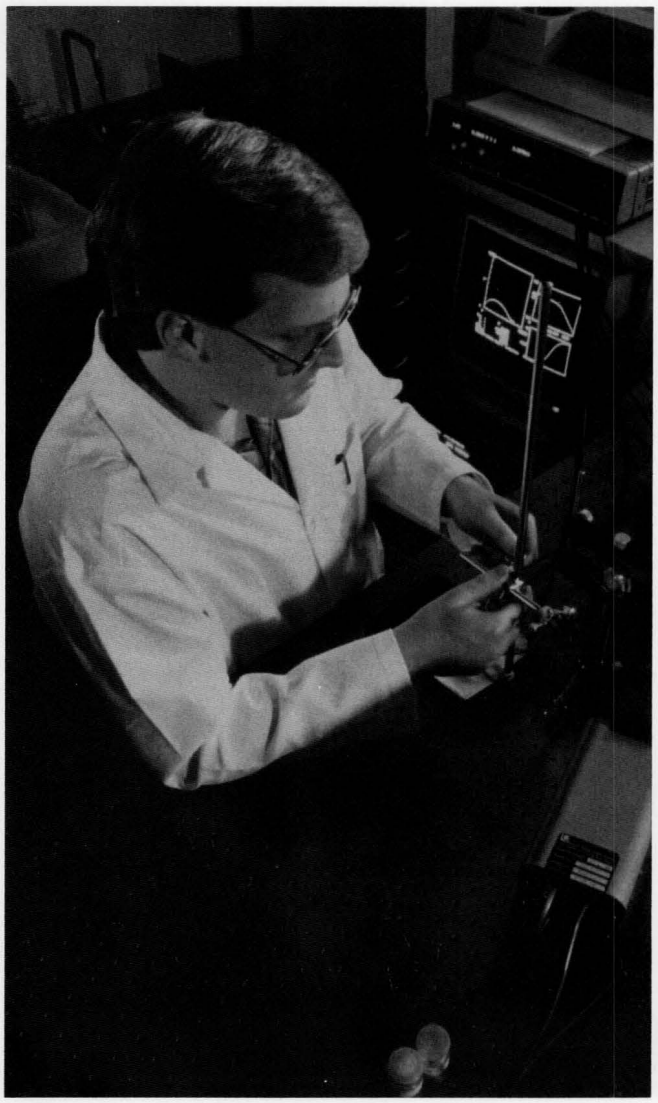

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IOANNIS BITSANIS • *Molecular Modeling of Interfaces*

SEYMOUR S. BLOCK • *Biotechnology*

OSCAR D. CRISALLE • *Electronic Materials, Process Control*

RICHARD B. DICKINSON • *Biomedical Engineering*

RAY W. FAHIEN • *Transport Phenomena, Reactor Design*

ARTHUR L. FRICKE • *Polymers, Pulp & Paper Characterization*

GAR HOFLUND • *Catalysis, Surface Science*

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

DALE KIRMSE • *Computer Aided Design, Process Control*

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

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

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GERALD WESTERMANN-CLARK • *Electrochemical Engineering, Bioseparations*

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University of Florida
Gainesville, Florida 32611
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M.S. and Ph.D. Programs

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- Chemical Vapor Deposition
- Composite Materials
- Complex Fluids
- Phase Transitions
- Macromolecular Phenomena
- Macromolecular Transport in Polymer Gel Media
- Polymer Processing
- Semiconductor and Superconductor Processing
- Thermodynamics

Bioengineering

- Biocatalysis
- Bioseparations
- Bioinformatics

Process Synthesis and Control

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

Surface Science, Catalysis and Inorganic Materials

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

Other Areas

- Applied and Computational Mathematics
- Air and Water Pollution Control

Faculty

Pedro Arce Ph.D.
Purdue University, 1990

Ravi Chella Ph.D.
University of Massachusetts, 1984

David Edelson Ph.D.
Yale University, 1949

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

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

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

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

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

Michael Peters Ph.D.
Ohio State University, 1981

Sam Riccardi Ph.D.
Ohio State University, 1949

John Telotte Ph.D.
University of Florida, 1985

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

*Afiliate Faculty

For Information Write to:

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

Georgia Tech

CHEMICAL ENGINEERING

The Faculty and Their Research

Polymer science and engineering

S. Abhiraman

Heterogeneous catalysis, surface chemistry, reaction kinetics

Pradeep K. Agrawal

Process design and control, spouted-bed reactors

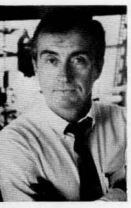
Yaman Arkun

Microelectronics, polymer processing

Sue Ann Bidstrup

Molecular thermodynamics, chemical kinetics, separations

Charles A. Eckert



Reactor design, catalysis

illiam R. Ernst

Mechanics of aerosols, buoyant plumes and jets

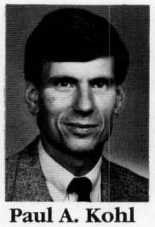
Larry J. Forney

Heat transport phenomena, fluidization

Charles W. Gorton

Pulp and paper

Jeffrey S. Hsieh



Photochemical processing, chemical vapor deposition

Paul A. Kohl

Molecular modeling of polymeric materials

eter J. Ludovice

Aerocolloidal systems, interfacial phenomena, fine-particle technology

Michael J. Matteson

Polymer engineering, energy conservation, economics

John D. Muzzy

Biomechanics, mammalian cell structures

Robert M. Nerem

Emulsion polymerization, latex technology

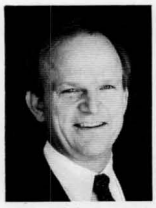
Gary W. Poehlein

Optimal process design and scheduling

atthew J. Realff

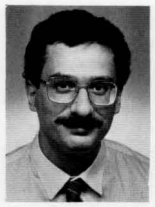
Biochemical engineering, mass transfer, reactor design

Ronnie S. Roberts



Separation processes, crystallization

Ronald W. Rousseau



Biochemical engineering, microbial and animal cell cultures

Athanassios Sambanis

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Robert J. Samuels

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Joseph Schork

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D. William Tedder

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Amyn S. Teja

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ark G. White

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Timothy M. Wick

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Jack Winnick

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Ajit P. Yoganathan

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Georgia Institute of Technology
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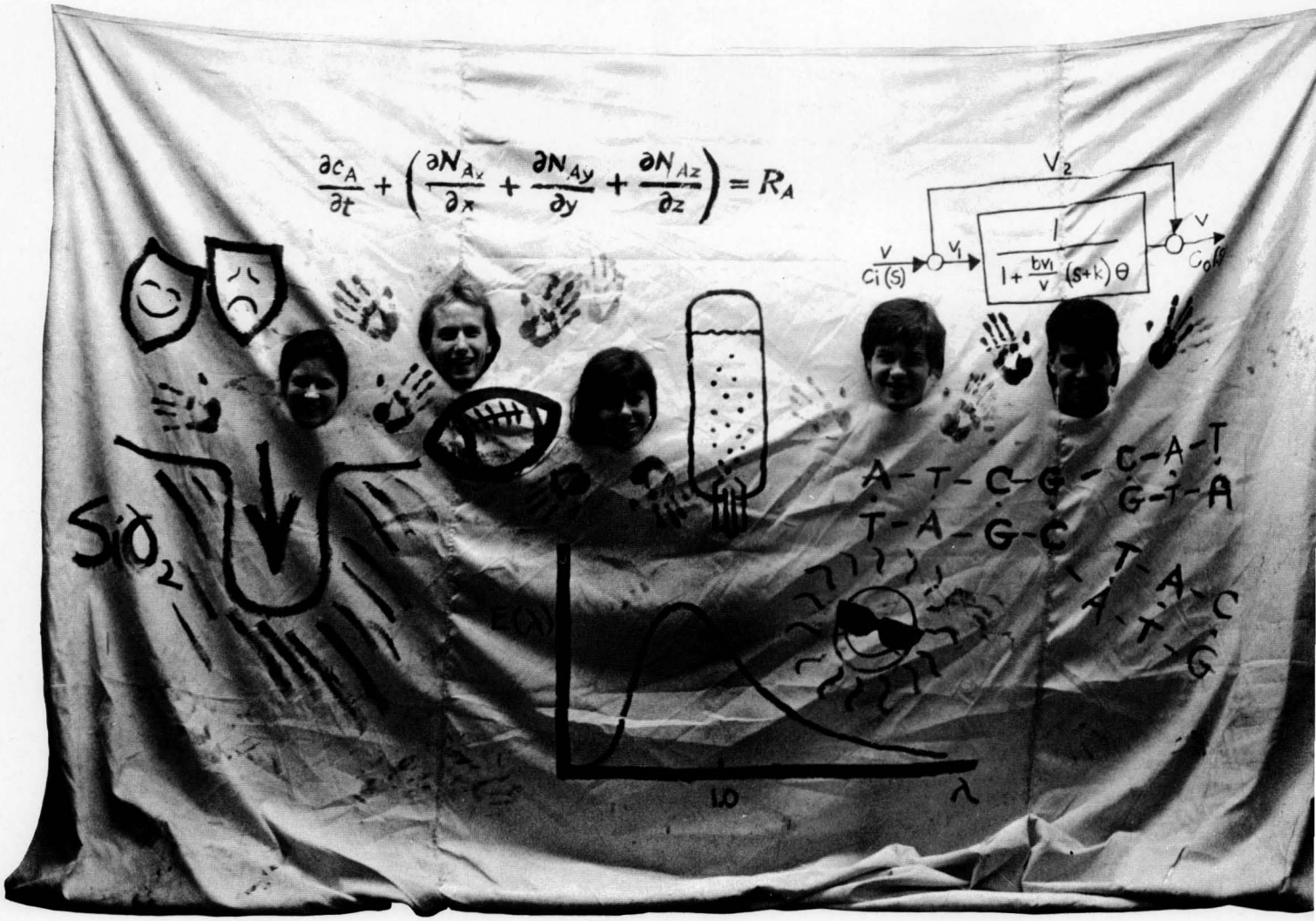

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Vemuri Balakotaiah
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Demetre Economou
Ernest Henley
John Killough
Dan Luss
Kishore Mohanty
Richard Pollard
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Raj Rajagopalan
Jim Richardson
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John H. Kiefer
Ph.D., Cornell University, 1961
Professor

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

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

Ludwig C. Nitsche
Ph.D., Massachusetts Institute of Technology, 1989
Assistant Professor

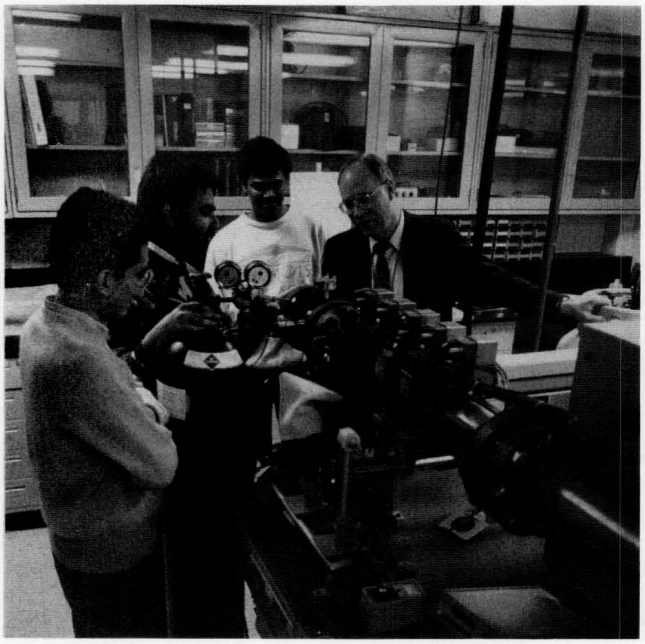
John Regalbuto
Ph.D., University of Notre Dame, 1986
Associate Professor

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

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

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

Bert L. Zuber
Ph.D., Massachusetts Institute of Technology, 1965
Professor



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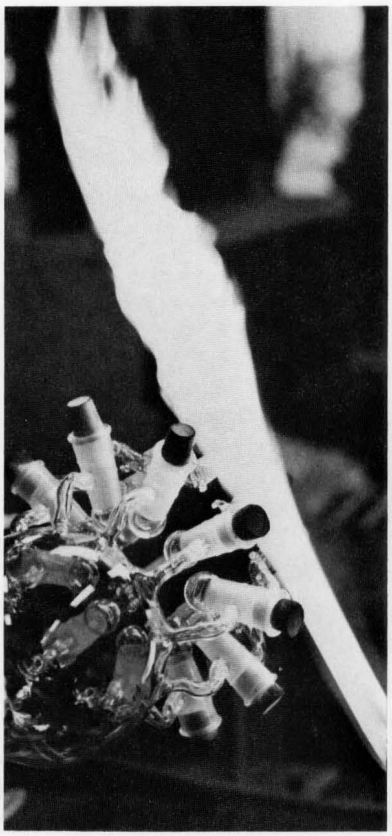

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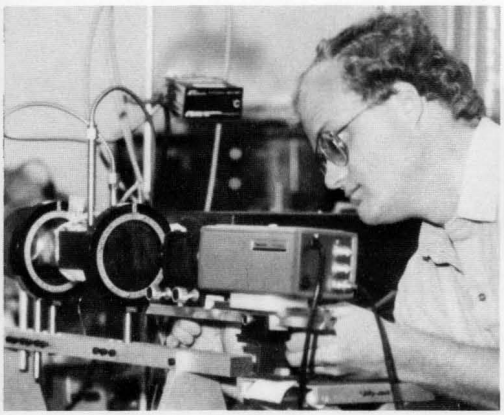

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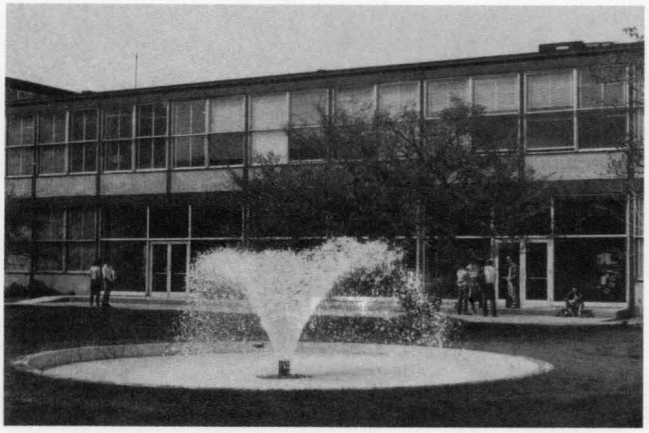

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  S.C. Johnson Polymer Assistant Professor
  Polymerization reaction engineering, and dynamic system analysis
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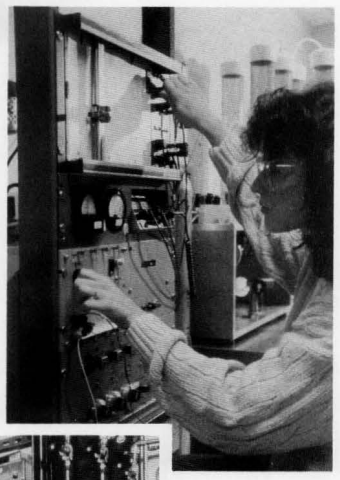

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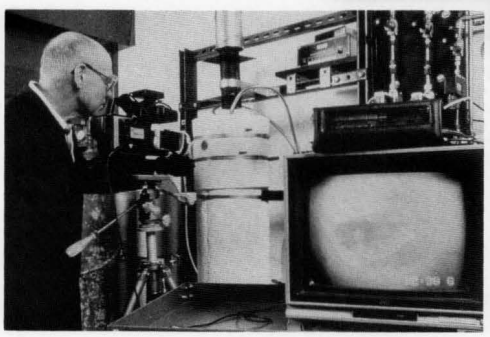

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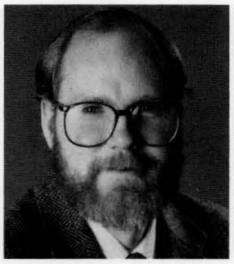
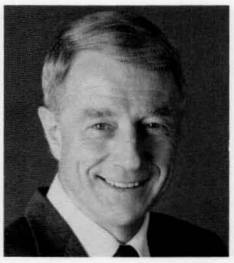
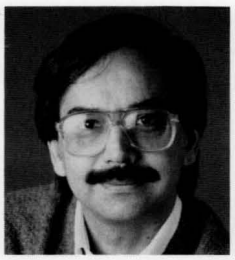


GREG CARMICHAEL
Chair; *U. of Kentucky, 1979*, Global Change/ Supercomputing



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

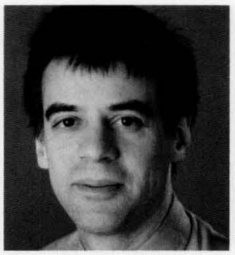
AUDREY BUTLER
U. of Iowa, 1989
Chemical Precipitation Processes



RAVI DATTA
UCSB, 1981
Reaction Engineering/ Catalyst Design

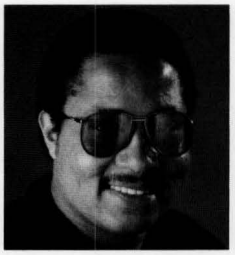
JONATHAN DORDICK
MIT, 1986,
Biocatalysis and Bioprocessing

DAVID LUERKENS
U. of Iowa, 1980
Fine Particle Science



DAVID MURHAMMER
U. of Houston, 1989
Animal Cell Culture

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



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

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Iowa City, Iowa 52242
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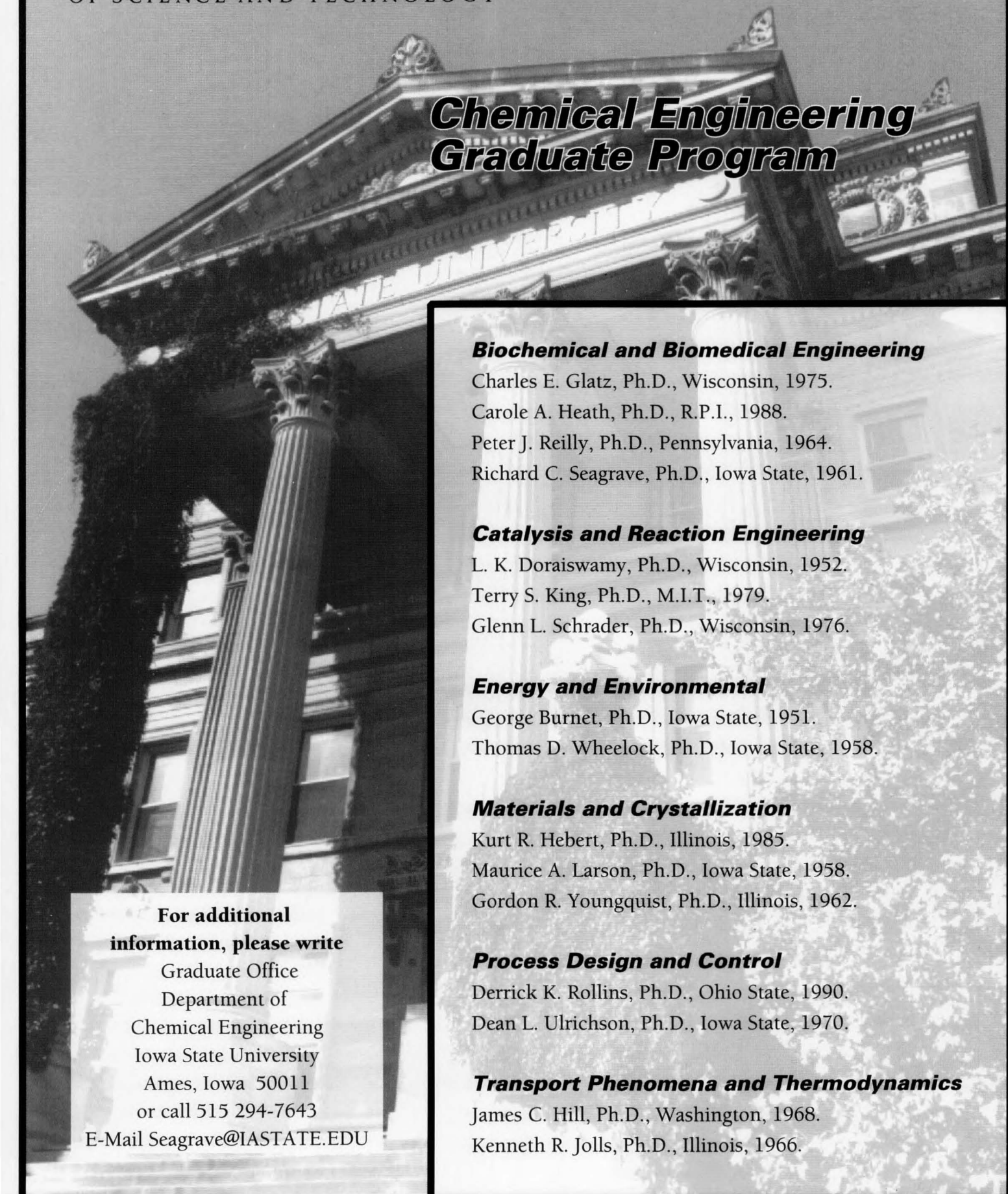

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Biochemical and Biomedical Engineering
Charles E. Glatz, Ph.D., Wisconsin, 1975.
Carole A. Heath, Ph.D., R.P.I., 1988.
Peter J. Reilly, Ph.D., Pennsylvania, 1964.
Richard C. Seagrave, Ph.D., Iowa State, 1961.

Catalysis and Reaction Engineering
L. K. Doraiswamy, Ph.D., Wisconsin, 1952.
Terry S. King, Ph.D., M.I.T., 1979.
Glenn L. Schrader, Ph.D., Wisconsin, 1976.

Energy and Environmental
George Burnet, Ph.D., Iowa State, 1951.
Thomas D. Wheelock, Ph.D., Iowa State, 1958.

Materials and Crystallization
Kurt R. Hebert, Ph.D., Illinois, 1985.
Maurice A. Larson, Ph.D., Iowa State, 1958.
Gordon R. Youngquist, Ph.D., Illinois, 1962.

Process Design and Control
Derrick K. Rollins, Ph.D., Ohio State, 1990.
Dean L. Ulrichson, Ph.D., Iowa State, 1970.

Transport Phenomena and Thermodynamics
James C. Hill, Ph.D., Washington, 1968.
Kenneth R. Jolls, Ph.D., Illinois, 1966.

For additional information, please write
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Iowa State University
Ames, Iowa 50011
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Bala Subramaniam (Ph.D., Notre Dame)
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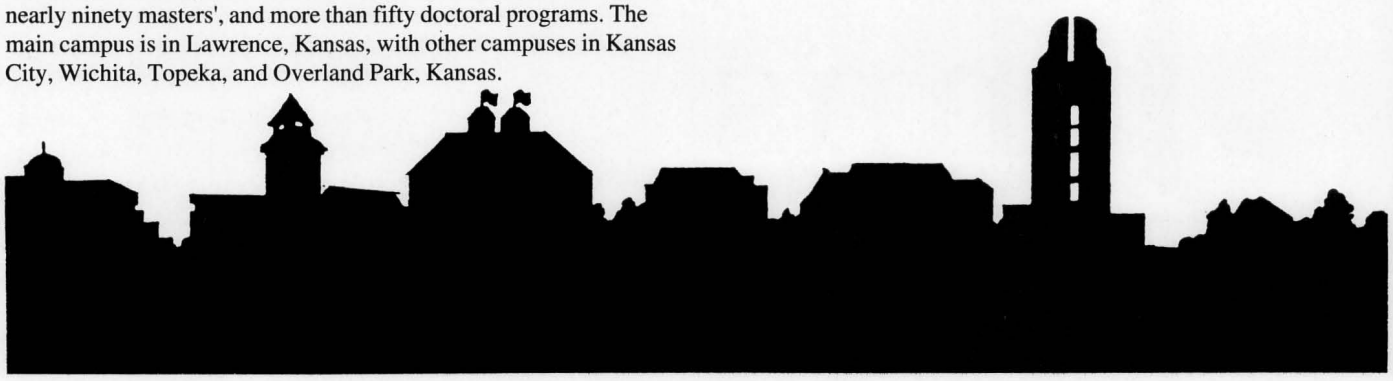

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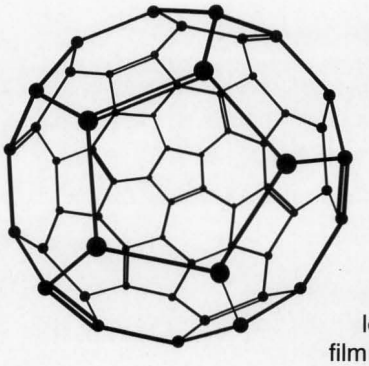

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Ph.D. Illinois Inst. of Technology
Professeur titulaire

ABDELHAMID SAYARI
Ph.D. Tunis/Lyon
Professeur adjoint

JULES THIBAULT
Ph.D. McMaster
Professeur titulaire

LEHIGH UNIVERSITY

We promise the challenge . . .

Synergistic, interdisciplinary research in. . .

- Biochemical Engineering
- Catalytic Science & Reaction Engineering
- Environmental Engineering
- Interfacial Transport
- Materials Synthesis Characterization & Processing
- Microelectronics Processing
- Polymer Science & Engineering
- Process Modeling & Control
- Thermodynamic Properties
- Two-Phase Flow & Heat Transfer

. . . leading to M.S. and Ph.D. degrees in chemical engineering and polymer science and engineering

Highly attractive financial aid packages, which provide tuition and stipend, are available.

Living in Bethlehem, PA, allows easy access to cultural and recreational opportunities in the New York-Philadelphia area.

Additional information and applications may be obtained by writing to:

Dr. Hugo S. Caram
Chairman, Graduate Admissions Committee
Department of Chemical Engineering
Lehigh University
111 Research Drive
Iacocca Hall
Bethlehem, PA 18015

Philip A. Blythe (University of Manchester)
fluid mechanics • heat transfer • applied mathematics

Hugo S. Caram (University of Minnesota)
gas-solid and gas-liquid systems • optical techniques • reaction engineering

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

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

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

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

Dennis W. Hess (Lehigh University)
microelectronics processing • thin film science and technology

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

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

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

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

Maria M. Santore (Princeton University)
polymers adsorption processes and blend stability

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

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

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

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

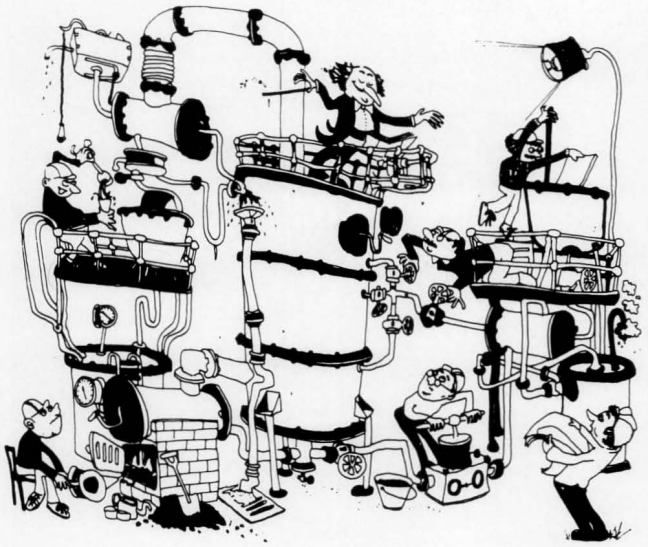
Harvey G. Stenger, Jr. (Massachusetts Institute of Technology)
reactor engineering

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

Leonard A. Wenzel, Emeritus (University of Michigan)
thermodynamics

LOUISIANA STATE UNIVERSITY

CHEMICAL ENGINEERING GRADUATE SCHOOL



THE CITY

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

THE DEPARTMENT

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

DEPARTMENTAL FACILITIES

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

TO APPLY, CONTACT

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

FACULTY

J.R. COLLIER (Ph.D., Case Institute)
Polymers, Textiles, Fluid Flow

A.B. CORRIPIO (Ph.D., Louisiana State University)
Control, Simulation, Computer-Aided Design

K.M. DOOLEY (Ph.D., University of Delaware)
Heterogeneous Catalysis, Reaction Engineering

G.L. GRIFFIN (Ph.D., Princeton University)
Electronic Materials, Surface Chemistry

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.A.HENSON (Ph.D., UC Santa Barbara)
Nonlinear and Biological Systems Control

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. OCONE (Ph.D., Princeton University)*
Applied Mathematics, Fluid Mechanics

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

D.M. WETZEL (Ph.D., University of Delaware)
Physical Properties, Hazardous Wastes

* *Visiting Professor*

FINANCIAL AID

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

University of Maine

• Faculty and Research Interests •

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

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

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

JOSEPH M. GENCO Ph.D. (Ohio State)
Acting Chair
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

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

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

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

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

Programs and • Financial Support •

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

• The University •

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

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

Call Collect or Write

Doug Bousfield
Department of Chemical Engineering
Jenness Hall, Box B • University of Maine
Orono, Maine 04469-5737
(207) 581-2300

University of Maryland

College Park

Location

The University of Maryland at 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.

Degrees Offered

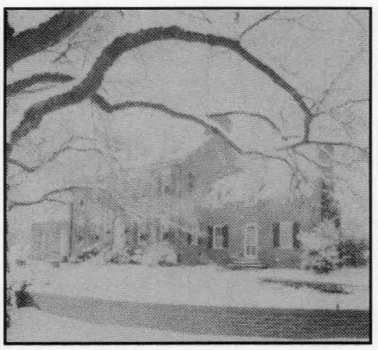
M.S. and Ph.D. programs in Chemical Engineering

Financial Aid Available

Teaching and Research Assistantships at $13,160/yr., plus tuition

Faculty:

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



Research Areas:

Aerosol Science
Artificial Intelligence
Biochemical Engineering
Multiphase Flow
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

UMBC
University of Maryland
Baltimore County

Graduate Study in BIOCHEMICAL ENGINEERING for Engineering and Science Majors

EMPHASIS

The Department of Chemical and Biochemical Engineering at UMBC offers graduate programs leading to M.S. and Ph.D. degrees in Chemical Engineering. Our research is heavily focused in biochemical and bioprocess engineering and covers a wide range of areas from fermentation,cell culture, downstream processing,drug delivery, protein engineering and protein stability. Unique programs in the Regulatory-Engineering interface of bioprocessing are offered as well.

FACILITIES

The Department offers state-of-the-art facilities for faculty and graduate student research. These modern facilities have been developed primarily in the last six years and comprise 6,000 square feet of laboratory space in the Technology Research Center plus 7,000 square feet of departmental laboratories in the new Engineering and Computer Science building, a $26 million facility opened in the Fall of 1992.

LOCATION

UMBC is located in the Baltimore-Washington corridor and within easy access to both metropolitan areas. A number of government research facilities such as NIH, FDA, USDA, NSA and a large number of biotechnology companies are located nearby and provide excellent opportunities for research interactions.

FACULTY

D. F. Bruley, Ph.D. ***Tennessee***
Biodownstream processing and processes in the microcirculation; Process simulation and control.

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

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

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.

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

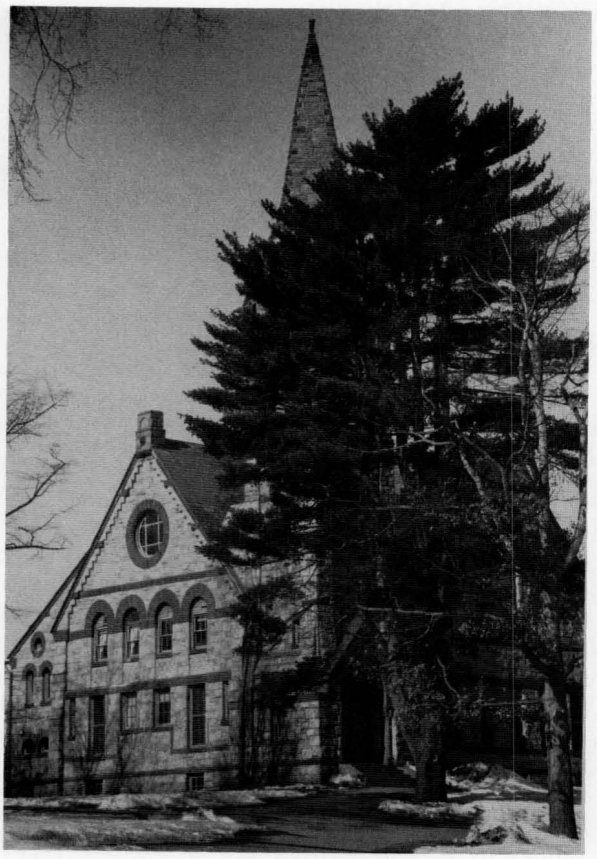
* *Joint appointment with the Maryland Biotechnology Institute*
** *Adjunct Professor/Eminent Scholar*

FOR FURTHER INFORMATION CONTACT:

Graduate Program Coordinator
Department of Chemical and Biochemical Engineering
University of Maryland Baltimore County
5401 Wilkens Avenue
Baltimore, Maryland 21228-5398
Phone:(410) 455-3400
FAX:(410) 455-1049

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)*
R. L. Laurence, Ph.D. *(Northwestern)*
M. F. Malone, Ph.D. *(Massachusetts)*
P. A. Monson, Ph.D. *(London)*
K. M. Ng, Ph.D. *(Houston)*
J. W. van Egmond *(Stanford)*
D. G. Vlachos, Ph.D. *(Minnesota)*
P. R. Westmoreland, Ph.D. *(M.I.T.)*
H. H. Winter, Ph.D. *(Stuttgart)*

Current Areas of Research

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

Design and Control Center

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

Financial Support

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

Location

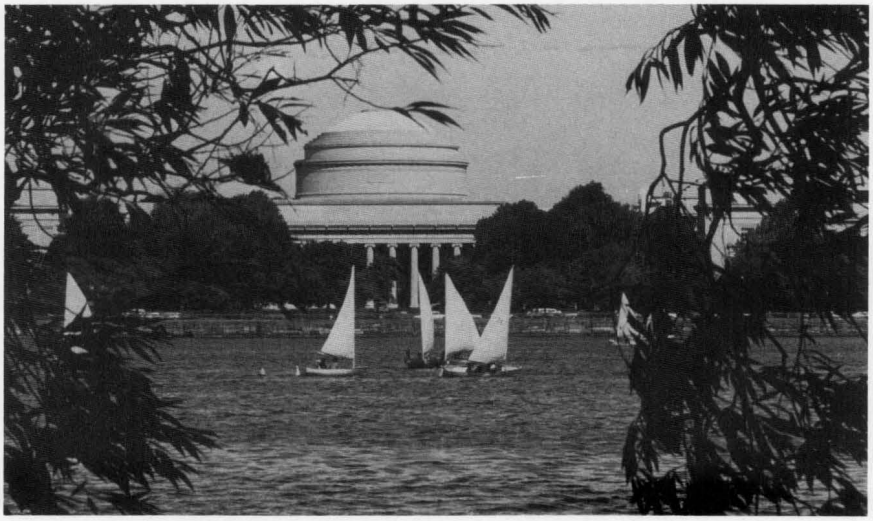
The Amherst Campus of the University is in a small New England town in Western Massachusetts. Set amid farmland and rolling hills, the area offers pleasant living conditions and extensive recreational facilities.

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

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

CHEMICAL ENGINEERING AT

MIT



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

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

RESEARCH AREAS

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

FOR MORE INFORMATION CONTACT

Chemical Engineering Graduate Office, 66-366
Massachusetts Institute of Technology, Cambridge, MA 02139-4307
Phone: (617) 253-4579; FAX: (617) 253-9695
E-Mail: info@chemegrad.mit.edu

FACULTY

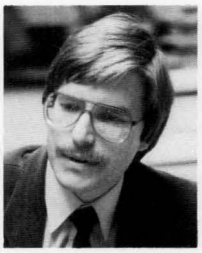
R.A. Brown, ***Department Head***
R.C. Armstrong
P.I. Barton
E.D. Blankschtein
H. Brenner
L.G. Cima
R.E. Cohen
C.K. Colton
C.L. Cooney
W.M. Deen
L.B. Evans
K.K. Gleason
P.T. Hammond
J.G. Harris
T.A. Hatton
J.B. Howard
K.F. Jensen
P.E. Laibinis
R.S. Langer
G.J. McRae
E.W. Merrill
G.C. Rutledge
A.F. Sarofim
H.H. Sawin
K.A. Smith
Ge. Stephanopoulos
Gr. Stephanopoulos
M.F. Stephanopoulos
J.W. Tester
P.S. Virk
D.I.C. Wang
J.Y. Ying

Chemical Engineering at

The University of Michigan

Faculty

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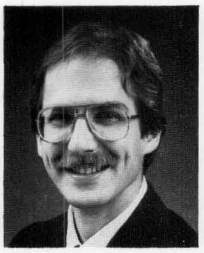
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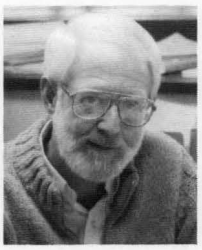
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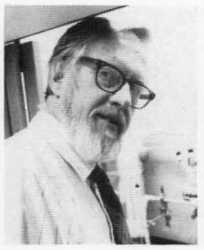
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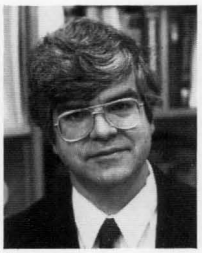
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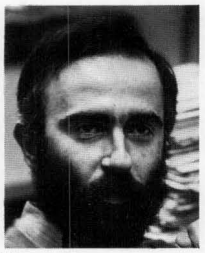
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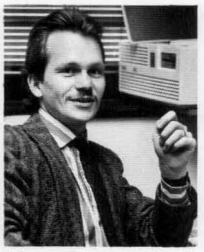
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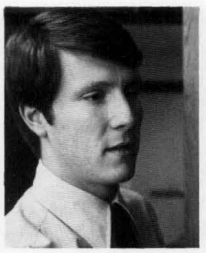
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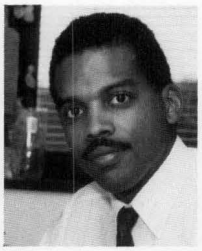
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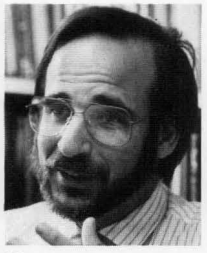
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For More Information, Contact:

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

GRADUATE STUDY IN CHEMICAL ENGINEERING AT

MICHIGAN STATE UNIVERSITY

The Department of Chemical Engineering offers Graduate Programs leading to M.S. and Ph.D. degrees in Chemical Engineering. The faculty conduct fundamental and applied research in a variety of Chemical Engineering disciplines. The Michigan Biotechnology Institute, the Composite Materials and Structures Center, and the Crop and Food 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 $14,658 per year plus a tuition waiver of six credits for Fall and Spring Semesters, four credits for Summer Semester. Theses may be written on the subject covered by the research assistantship.

FELLOWSHIPS • Available appointments pay up to $18,000 per year.

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, Crystallization from Solution

➤ **D. M. BRIEDIS** • *Ph.D., 1981, Iowa State University*
Surface Phenomena in Crystallization Processes, Biochemical and Food Engineering, Bioadhesion

➤ **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

➤ **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*
Polymer Blends and Alloys, Biodegradable Plastics, Low-Cost Composites Using Recycled/Reclaimed and Natural Polymers, Biodegradation and Composting Studies

➤ **R. Y. OFOLI** • *Ph.D., 1994, Carnegie Mellon University*
Colloid and Interface Science, Colloid Stability, Adsorption of Proteins at the Liquid-Liquid Interface

➤ **C. A. PETTY** • *Ph.D., 1970, University of Florida*
Fluid Mechanics, Turbulent Transport Phenomena, Solid-Fluid and Liquid-Liquid Separations, Polymer Composite Processing

➤ **A. B. SCRANTON** • *Ph.D., 1990, Purdue University*
Polymer Science and Engineering, Polymer Complexation and Network Formation, Applications of NMR Spectroscopy, Molecular Modeling, Crosslinking Polymerizations

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

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

FOR ADDITIONAL INFORMATION WRITE

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

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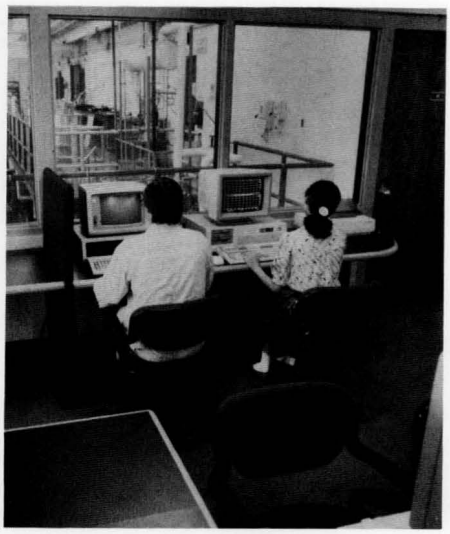
Michigan Technological University



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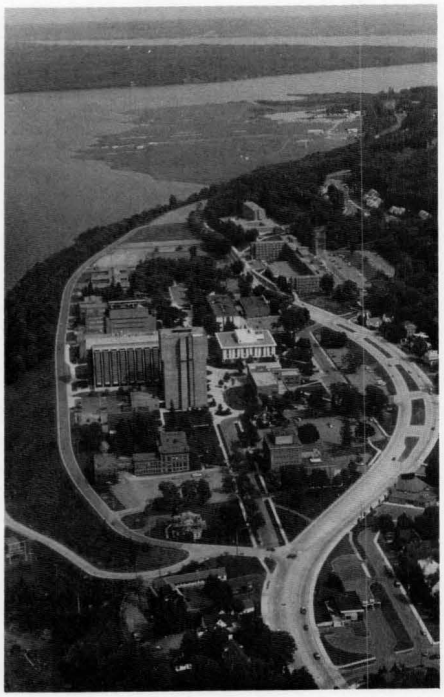
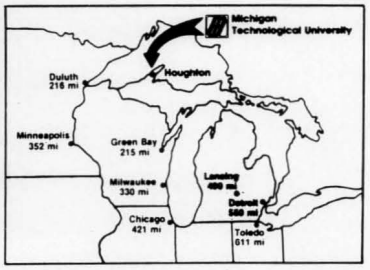




CONTACT

Department of Chemical Engineering
Michigan Technological University
1400 Townsend Drive
Houghton, MI 49931-1295
906/487-3132
FAX 906/487-3213

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

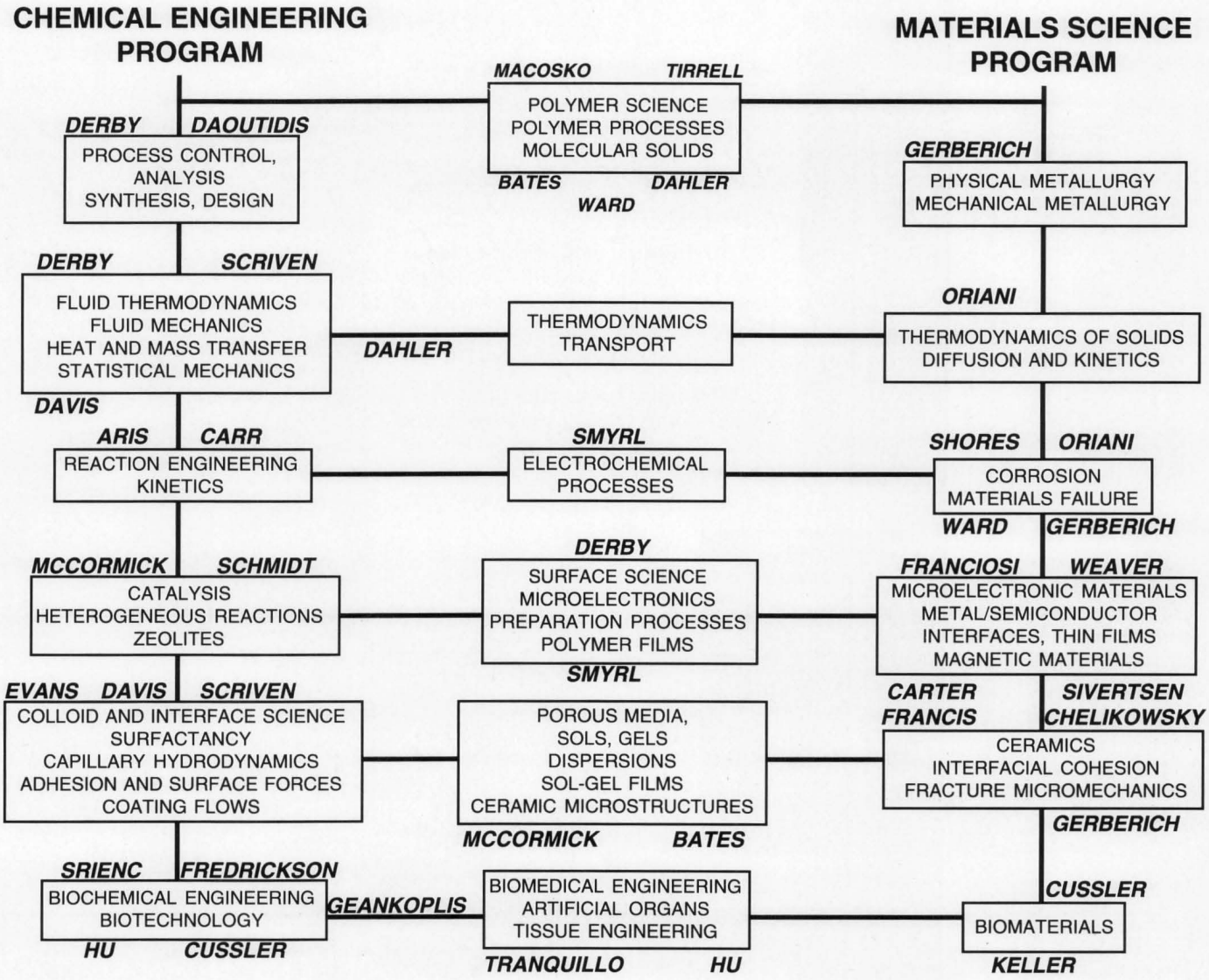
Surface science, sol-gel processing
Michael E. Mullins, Professor
Ph.D., Rochester, 1983

Polymer Science, polymer and composite processing
John G. Williams, Professor
Ph.D., Melbourne University

Chemical Process Safety
Daniel A. Crowl, Professor
Ph.D., University of Illinois Urbana, 1975

UNIVERSITY OF MINNESOTA

Chemical Engineering and Materials Science



THE FACULTY

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

For information and application forms, write:

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

Department of Chemical Engineering

UMR

MISSOURI'S TECHNOLOGICAL UNIVERSITY

UNIVERSITY OF MISSOURI-ROLLA

M.S. and Ph.D. Degrees

FACULTY AND RESEARCH INTERESTS

N. L. BOOK ***(Ph.D., Colorado)***
- Computer Aided Process Design • Bioconversion

O. K. CROSSER ***(Ph.D., Rice)***
- Transport Properties • Adsorption

D. FORCINITI ***(Ph.D., North Carolina State)***
- Bioseparations • Thermodynamics
- Statistical Mechanics

J. W. JOHNSON ***(Ph.D. Missouri)***
- Electrode Reactions • Adsorption

A. I. LIAPIS ***(Ph.D., ETH-Zurich)***
- Adsorption • Affinity Chromatography • Perfusion Chromatography • Transport Phenomena
- Lyophilization (Freeze Drying)

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

N. C. MOROSOFF ***(Ph.D., Brooklyn Polytech)***
- Plasma Polymerization • Membranes

P. NEOGI ***(Ph.D., Carnegie-Mellon)***
- Interfacial and Transport Phenomena

G. K. PATTERSON ***(Ph.D., Missouri-Rolla)***
- Mixing • Polymer Rheology • Computational Fluid Dynamics and Turbulent Transport

X B REED, JR. ***(Ph.D., Minnesota)***
- Fluid Mechanics • Drop and Particle Mechanics
- Transport Phenomena • Turbulence Structure
- Turbulence Modeling, including Reactions

S. L. ROSEN ***(Ph.D., Cornell)***
- Polymerization Reactions • Applied Rheology
- Polymeric Materials

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

R. C. WAGGONER ***(Ph.D., Texas A&M)***
- Multistage Mass Transfer Operations • Distillation
- Extraction • Process Control

R. M. YBARRA ***(Ph.D., Purdue)***
- Rheology of Polymer Solutions • Chemical Reaction Kinetics

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

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

The University of New Mexico

Research Areas

Toxic and radioactive waste management

Superconducting ceramics

Microelectronics processing

Heterogeneous catalysis

Laser-enhanced CVD

Sol-gel and colloidal processing of ceramics

Biomedical engineering

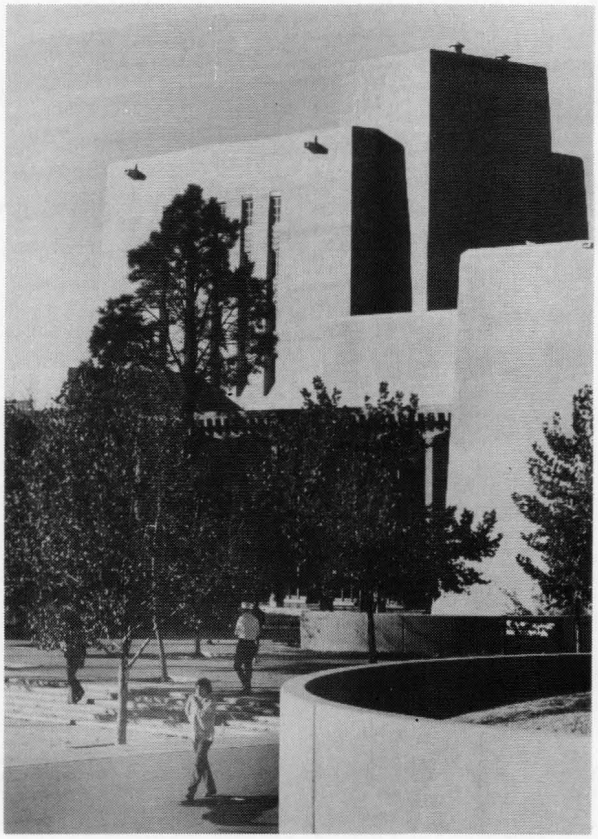
Plasma science

Surface science

Aerosol physics

Materials characterization

Uncertainty and risk assessment



Faculty

Harold Anderson

C. Jeffrey Brinker

Abhaya K. Datye

David Kauffman

Toivo T. Kodas

Ronald E. Loehman

Gabriel P. López

Richard W. Mead

H. Eric Nuttall

Douglas M. Smith

Timothy L. Ward

Ebtisam S. Wilkins

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

The Chemical Engineering Department offers financial aid in the form of research assistantships paying $10-15,000 per year, plus tuition.

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:
Timothy L. Ward, Graduate Advisor
Department of Chemical and Nuclear Engineering
The University of New Mexico
Albuquerque, NM 87131-1341
Phone (505) 277-5431

North Carolina

State University

DEPARTMENT OF CHEMICAL ENGINEERING

Biochemical Engineering
Catalysis, Kinetics, and Reaction Engineering
Computer-Aided Design and Manufacturing
Electronic Materials
Electrochemical Engineering
Environmental Engineering
Polymer Science and Engineering
Thermodynamics and Computer Simulation

FACULTY AND THEIR RESEARCH INTERESTS

Ruben G. Carbonell • ***Princeton***
Bioseparations; Colloid and Surface Science; Multiphase Transport Phenomena

Peter S. Fedkiw • ***Cal-Berkeley***
Electrochemical Engineering; Electrocatalysis

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 • ***Cal-Berkeley***
Polymer Physical Chemistry

Christine S. Grant • ***Georgia Tech***
Colloid and Surface Science; Environmental Engineering

Carol K. Hall • ***Stony Brook***
Statistical Thermodynamics; Computer Simulation; Polymers; Protein Folding

Harold B. Hopfenberg • ***MIT***
Transport and Aging in Glassy Polymers; Controlled Release; Membranes; Barrier Packaging

Saad Khan • ***MIT***
Polymer Rheology; Rheology of Reactive Polymer Solutions and Melts; Polymer Spectroscopy

Robert M. Kelly • ***NC State***
Bioenergetics and Physiology of Microorganisms from Extreme Environments; Biocatalysis

Peter K. Kilpatrick • ***Minnesota***
Interfacial and Surface Science; Biotechnology

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; Photochemical Engineering

Michael R. Overcash • ***Minnesota***
Environmental Engineering; Improved Manufacturing Productivity by Waste Reduction

Gregory N. Parsons • ***N.C. State***
Semiconductor and Insulator Growth Chemistry; Physics of Amorphous Materials and Devices

Steven W. Peretti • ***Caltech***
Genetic and Metabolic Engineering; Microbial, Plant and Animal Cell Culture; Bioremediation

George W. Roberts • ***MIT***
Heterogeneous Catalysis; Reaction Kinetics and Engineering; Pollution Prevention

C. John Setzer • ***Ohio State***
Plant and Process Economics and Management

Vivian T. Stannett, Emeritus • ***Brooklyn Poly***
Pure and Applied Polymer Science

Robert Thorogood • ***London***
Process Design and Modeling; Adsorptive and Membrane Separations

Inquiries to:
Professor Robert M. Kelly, Director of Graduate Studies, (919) 515-6396

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

Chemical Engineering at

Northwestern University

S. George Bankoff, Ph.D., Purdue, 1955
Two-phase heat transfer, fluid mechanics

Wesley R. Burghardt, Ph.D., Stanford, 1990
Polymer science, rheology

John B. Butt, D.Eng., Yale, 1960
Chemical reaction engineering

Stephen H. Carr, Ph.D., Case Western Reserve, 1970
Solid state properties of polymers

Buckley Crist, Jr., Ph.D., Duke, 1966
Polymer science

Joshua S. Dranoff, Ph.D., Princeton, 1960
Chemical reaction engineering, chromatographic separations

Thomas K. Goldstick, Ph.D., Berkeley, 1966
Biomedical engineering, oxygen transport in the human body

Harold H. Kung, Ph.D., Northwestern, 1974
Kinetics, heterogeneous catalysis

Richard S. H. Mah, Ph.D., London, 1961
Computer-aided process planning, design and analysis

Michael L. Mavrovouniotis, Ph.D., MIT, 1989
Computer-aided process engineering and pathway analysis

William M. Miller, Ph.D., Berkeley, 1987
Cell culture for biotechnology and medicine

Lyle F. Mockros, Ph.D., Berkeley, 1962
Biomedical engineering, fluid mechanics in biological systems

Monica Olvera de la Cruz, Ph.D., Cambridge, 1984
Statistical mechanics in polymer systems

Julio M. Ottino, Ph.D., Minnesota, 1979
Fluid mechanics, chaos, mixing in materials processing

E. Terry Papoutsakis, Ph.D., Purdue, 1980
Biotechnology of animal and microbial cells

Mark A. Petrich, Ph.D., Berkeley, 1987
Environmental engineering, electronic materials, solid state NMR

Bruce E. Rittmann, Ph.D., Stanford, 1979
In situ bioremediation, biofilms

Gregory Ryskin, Ph.D., Caltech, 1983
Fluid mechanics, computational methods, polymeric liquids

Wolfgang M. H. Sachtler, Dr. rer.nat., Braunschweig, 1952
Heterogeneous catalysis

John M. Torkelson, Ph.D., Minnesota, 1983
Polymer science, membranes

For information and application to the graduate program, write

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

Phone (708) 491-2776
or (800) 848-5135 (U.S. only)

Chemical Engineering at Notre Dame

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

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

FACULTY

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

RESEARCH AREAS

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

For further information, write to:

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

THE OHIO STATE UNIVERSITY

GRADUATE STUDY IN

CHEMICAL ENGINEERING

If you are considering graduate school, here are four good reasons to enroll in chemical engineering at Ohio State:

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

For complete information on our programs, potential thesis topics, and degree requirements write or call collect: Professor Jacques L. Zakin, Department of Chemical Engineering, The Ohio State University, 140 W. 19th Avenue, Columbus, Ohio 43210-1180, (614) 292-6591.

Cutting Edge Research

Excellent Opportunities for Personal and Professional Growth

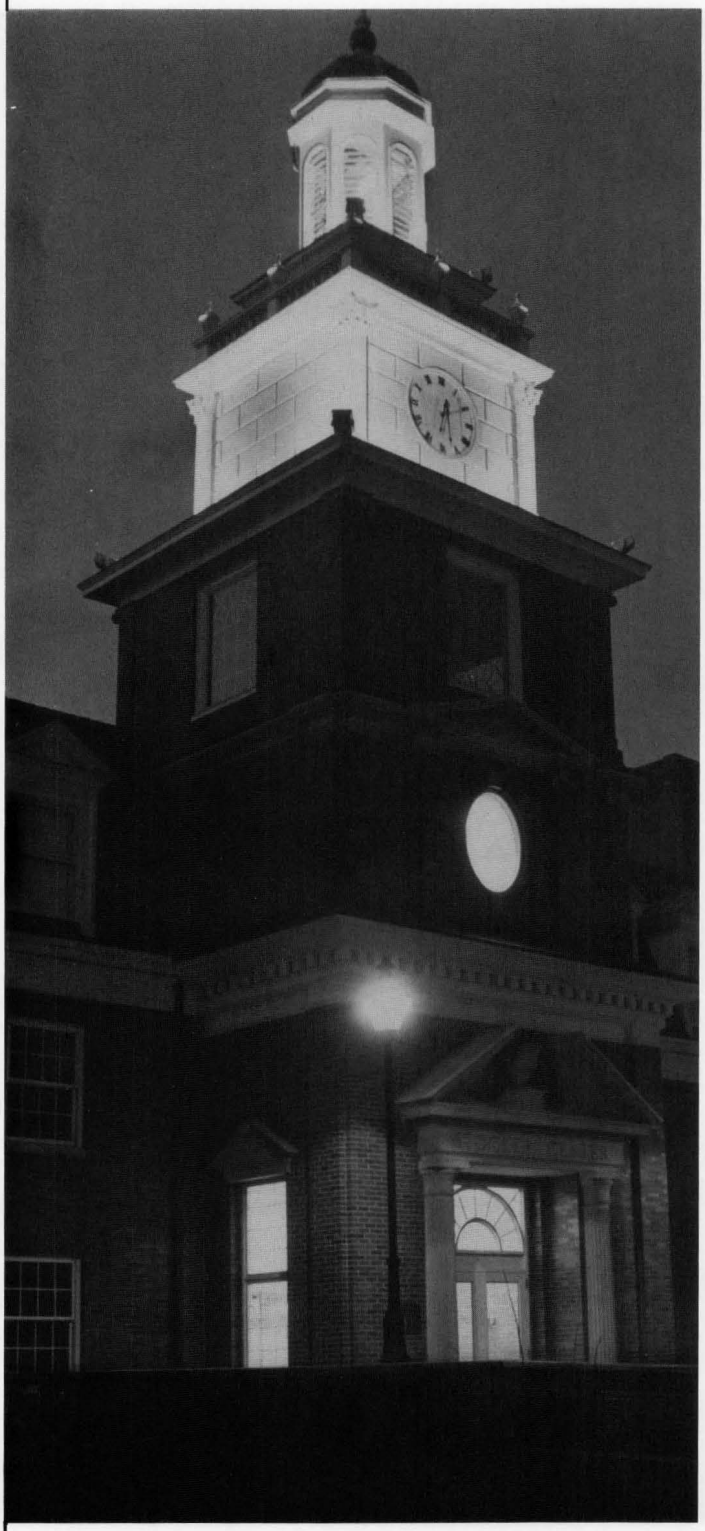
Close Relationships Between Graduate Students and Faculty

- **Bhavik Bakshi,** *Mass. Inst. Tech. 1992,* Process Control, Intelligent Controllers, Wavelet Neural Networks, Systems Integration, Artificial Intelligence in Design, Planning, and Analysis
- **Robert S. Brodkey,** *Wisconsin 1952,* Turbulence, Mixing, Image Analysis, Reactor Design, and Rheology
- **Jeffrey J. Chalmers,** *Cornell 1988,* Biochemical Engineering, Hydrodynamic Effects on Cells, Cell Separations, Biodegradation/Bioremediation
- **James F. Davis,** *Northwestern 1981,* Artificial Intelligence in Diagnosis and Control, Intelligent Control, Data Interpretation, Pattern Recognition, Neural Networks, Systems Integration, Model Integration
- **L. S. Fan,** *West Virginia 1975,* Fluidization, Powder Technology, Multiphase and Particulates Reaction Engineering, and Mathematical Modeling
- **Morton H. Friedman,** *Michigan 1961,* Biomedical Engineering and Hemodynamics
- **Harry C. Hershey,** *Missouri-Rolla 1965,* Thermodynamics and Environmental
- **Kurt W. Koelling,** *Princeton 1992,* Polymer Processing, Liquid Crystalline Polymers, Biodegradable Polymers, Polymer Rheology and Morphology
- **L. James Lee,** *Minnesota 1979,* Polymer Processing, Composite Manufacturing, and Thermoset Polymers
- **Umit S. Ozkan,** *Iowa State 1984,* Application of Heterogeneous Catalysis to Energy and Environmental Issues, Catalytic Materials, and Heterogeneous Kinetics
- **James F. Rathman,** *Oklahoma 1987,* Interfacial Phenomena, Surfactant Science, Rheology of Surfactant Systems
- **David L. Tomasko,** *Illinois 1992,* Intermolecular Interactions in Supercritical Fluids, Supercritical Fluid Extraction, Molecular Thermodynamics
- **Shang-Tian Yang,** *Purdue 1984,* Biochemical Engineering and Biotechnology, Fermentation Processes, and Kinetics
- **Jacques L. Zakin,** *New York 1959,* Surfactant and Polymer Drag Reduction, Micellar Structures, Rheology, and Emulsions

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

Ohio University

Chemical Engineering



Graduate Programs

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

Research Areas

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

Financial Aid

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

The Faculty

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

Ohio University is an affirmative action institution.

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

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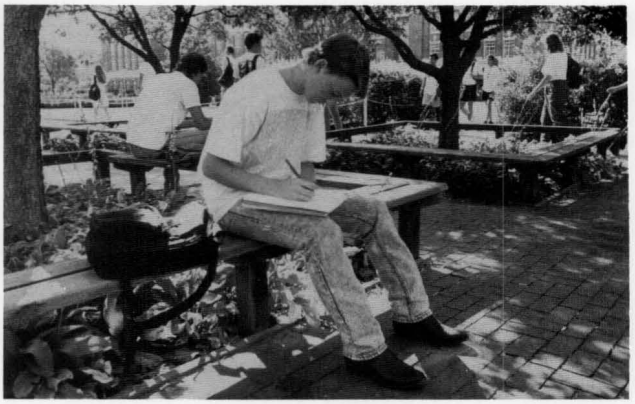
Oklahoma State University

"Where People Are Important"

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



Faculty

Kenneth J. Bell (Ph.D., University of Delaware)
Gary L. Foutch (Ph.D., University of Missouri-Rolla)
K.A.M. Gasem (Ph.D., Oklahoma State University)
Karen A. High (Ph.D., Pennsylvania State University)
Martin S. High (Ph.D., Pennsylvania State University)
A.J. Johannes (Ph.D., University of Kentucky)
Robert L. Robinson, Jr. (Ph.D., Oklahoma State University)
D. Alan Tree (Ph.D., University of Illinois)
Jan Wagner (Ph.D., University of Kansas)
James R. Whiteley (Ph.D., Ohio State University)

Research Areas

Adsorption
Air Pollution
Artificial Intelligence
Biochemical Processes
Corrosion
Design
Environmental Engineering
Fluid Flow
Gas Processing
Hazardous Wastes
Heat Transfer
Ion Exchange
Kinetics
Mass Transfer
Modeling
Phase Equilibria
Polymers
Process Control
Process Simulation
Thermodynamics

For more information contact

Graduate Coordinator
School of Chemical Engineering
Oklahoma State University
Stillwater, OK 74078

OREGON STATE UNIVERSITY

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

Our programs reflect not only traditional chemical engineering fields but also new technologies important to the Northwest's industries, such as electronic material processing, forest products, food science, and ocean products.

Oregon State is located only a short drive from the Pacific Ocean, white-water rivers, and hiking / skiing / climbing in the Cascade Mountains

FACULTY

W. J. Frederick	•	Chemical Recovery Technology (Pump and Paper), Combustion
T. M. Grace	•	Chemical Recovery Technology
M.K. Iisa	•	Combustion, Waste Minimization
G. N. Jovanovic	•	Fine Particle Processing, Transport Phenomena
S. Kimura	•	Reaction Engineering, High-Temperature Materials
J. G. Knudsen	•	Heat Transfer
M. D. Koretsky	•	Electronic Materials Processing
O. Levenspiel	•	Fluidization, Chemical Reaction Engineering
K. L. Levien	•	Process Optimization and Control
J. McGuire	•	Protein Adsorption, Biofilm Development
W. E. Rochefort	•	Rheology, Characterization of Polymers
G. L. Rorrer	•	Biochemical Reaction Engineering
C. E. Wicks	•	Mass Transfer

Competitive research and teaching assistantships are available.

For further information, write:

Chemical Engineering Department
Oregon State University • Gleeson Hall, Room 103
Corvallis, Oregon 97331-2702

PENN

UNIVERSITY of PENNSYLVANIA

University of Pennsylvania Chemical Engineering

Stuart W. Churchill
Combustion, thermoacoustic convection, Czochralski crystallization, rate processes

Russell J. Composto
Polymeric materials science, surface and interface studies

Gregory C. Farrington
Electrochemistry, solid state and polymer chemistry

William C. Forsman
Polymer science and engineering, graphite intercalation

Eduardo D. Glandt
Classical and statistical thermodynamics, random media

Raymond J. Gorte
Heterogeneous catalysis, surface science, zeolites

David J. Graves
Biochemical and biomedical engineering, bioseparations

Mitchell Litt
Biorheology, transport processes in biological systems, biomedical engineering

Alan L. Myers
Adsorption of gases and liquids, molecular simulations

Daniel D. Perlmutter
Chemical reactor design, gas-solid reactions, gel kinetics

John A. Quinn
Membrane transport, biochemical/biomedical engineering

Warren D. Seider
Process analysis, simulation, design, and control

Lyle H. Ungar
Artificial intelligence in process control, neural networks

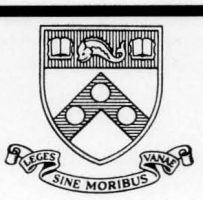
T. Kyle Vanderlick
Thin-film and interfacial phenomena

John M. Vohs
Surface science and heterogeneous catalysis

Paul B. Weisz
Molecular selectivity in chemical and life processes

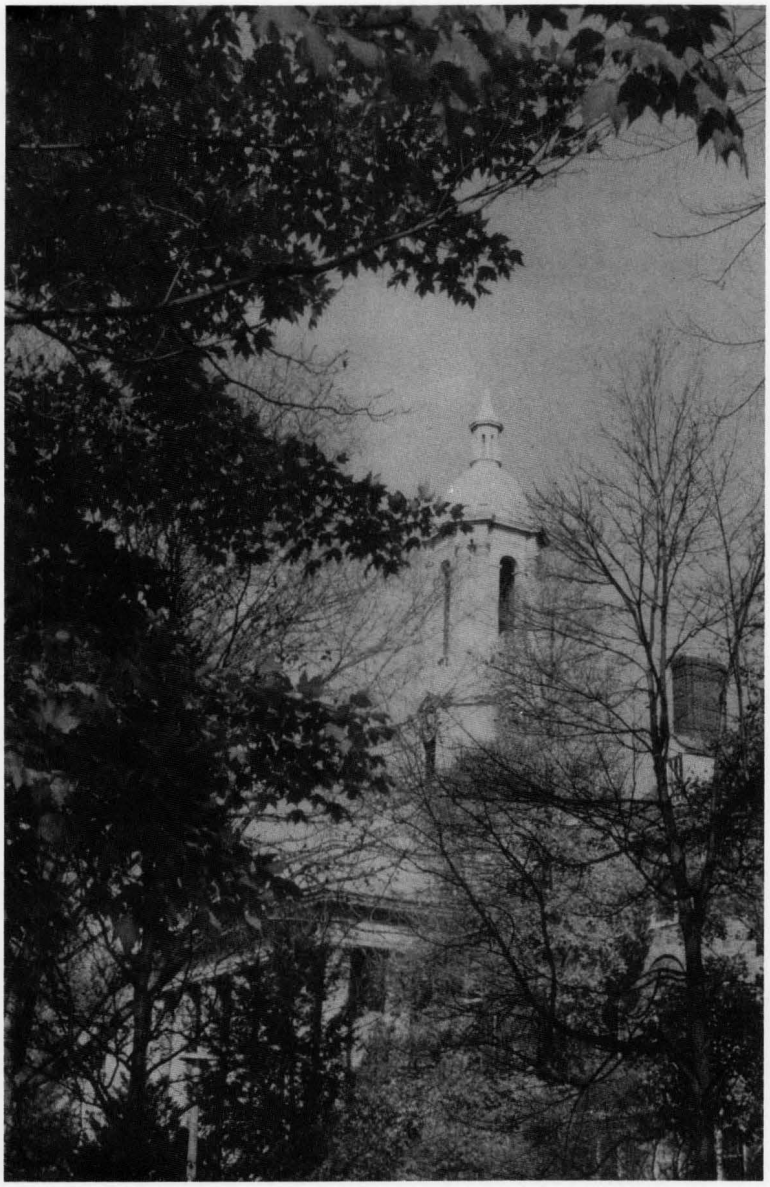
Pennsylvania's chemical engineering program is designed to be flexible while emphasizing the fundamental nature of chemical and physical processes. Students may focus their studies in any of the research areas of the department. The full resources of this Ivy League university, including the Wharton School of Business and one of this country's foremost medical centers, are available to students in the program. The cultural advantages, historical assets, and recreational facilities of a great city are within walking distance of the University.

For additional information, write:



Director of Graduate Admissions
Department of Chemical Engineering
311A Towne Building
University of Pennsylvania
Philadelphia, Pennsylvania 19104-6393

PENN STATE



Individuals holding the B.S. in chemistry or other related areas are encouraged to apply.

For more information, contact
Chairman, Graduate Admissions Committee
The Pennsylvania State University
Department of Chemical Engineering
158 Fenske Laboratory
University Park, PA 16802

Paul Barton (Penn State)
Separational Processes

Ali Borhan (Stanford)
Fluid Dynamics, Transport Phenomena

Alfred Carlson (Wisconsin)
Biotechnology, Bioseparations

Lance R. Collins (Penn)
Turbulent Flow, Combustion

Wayne Curtis (Purdue)
Plant Biotechnology

Ronald P. Danner (Lehigh)
Applied Thermodynamics, Adsorption Phenomena

Thomas E. Daubert *(Penn State)*
Applied Thermodynamics

J. Larry Duda (Delaware)
Polymers, Diffusion, Tribology, Fluid Mechanics, Rheology

John A. Frangos (Rice)
Biomedical Engineering, Biotechnology

Kristen Fichthorn (Michigan)
Statistical Mechanics, Surface Science, Catalysis

W. Patrick Hegarty (Michigan)
Plant Design

Arthur E. Humphrey (Columbia)
Biotechnology

Themis Matsoukas (Michigan)
Aerosol Processes, Colloidal Particles, Ceramic Powders

John R. McWhirter (Penn State)
Gas-Liquid Mass Transfer, Microencapsulation

R. Nagarajan (SUNY Buffalo)
Colloid and Polymer Science

Jonathan Phillips (Wisconsin)
Heterogeneous Catalysis, Surface Science

John M. Tarbell (Delaware)
Cardiovascular Fluid Mechanics and Mass Transfer, Turbulent Reacting Flows

James S. Ultman (Delaware)
Mass Transport in the Human Lung, Intensive Care Monitoring

M. Albert Vannice (Stanford)
Heterogeneous Catalysis

James S. Vrentas (Delaware)
Transport Phenomena, Applied Mathematics, Polymer Science

DEGREE PROGRAMS
PhD and MS in Chemical Engineering
MS in Petroleum Engineering
MS in Bioengineering

What is chemical engineering at Pitt?

A short answer:

applied enzymology
biochemical engineering
biotechnology
chemistry of fossil fuels
coal science
colloidal suspensions
combustion
flow through porous media
heterogeneous catalysis
kinetics
microemulsions
molecular thermodynamics
organometallic chemistry
petroleum engineering
phase equilibria
polymers
process design
protein engineering
reaction engineering
recycling technology
separation science
solids processing
superacids
supercritical fluids
surface chemistry
transport phenomena

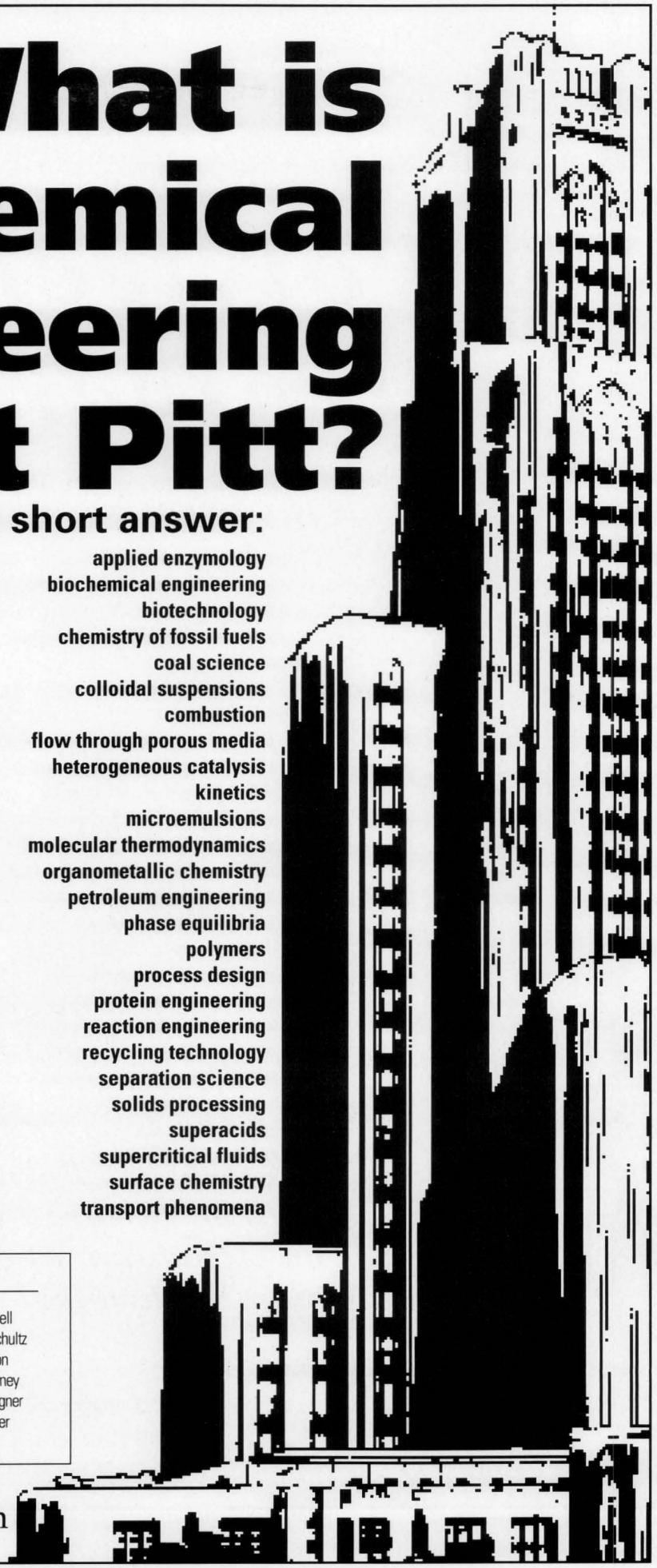
For a more detailed answer, and information about fellowships and applications, write or call the

Graduate Coordinator
Department of Chemical and Petroleum Engineering
1249 Benedum Hall
University of Pittsburgh
Pittsburgh,PA15261
412-624-9630

FACULTY

Mohammad M. Ataai	Dan Farcasiu	Alan J. Russell
Eric J. Beckman	James G. Goodwin, Jr.	Jerome S.Schultz
Alan J. Brainard	Gerald D. Holder	Sindee Simon
Edward Cape	George E. Klinzing	John W.Tierney
Shiao-Hung Chiang	George Marcelin	William Wagner
James T. Cobb, Jr.	Badie I. Morsi	Irving Wender
Robert M. Enick		

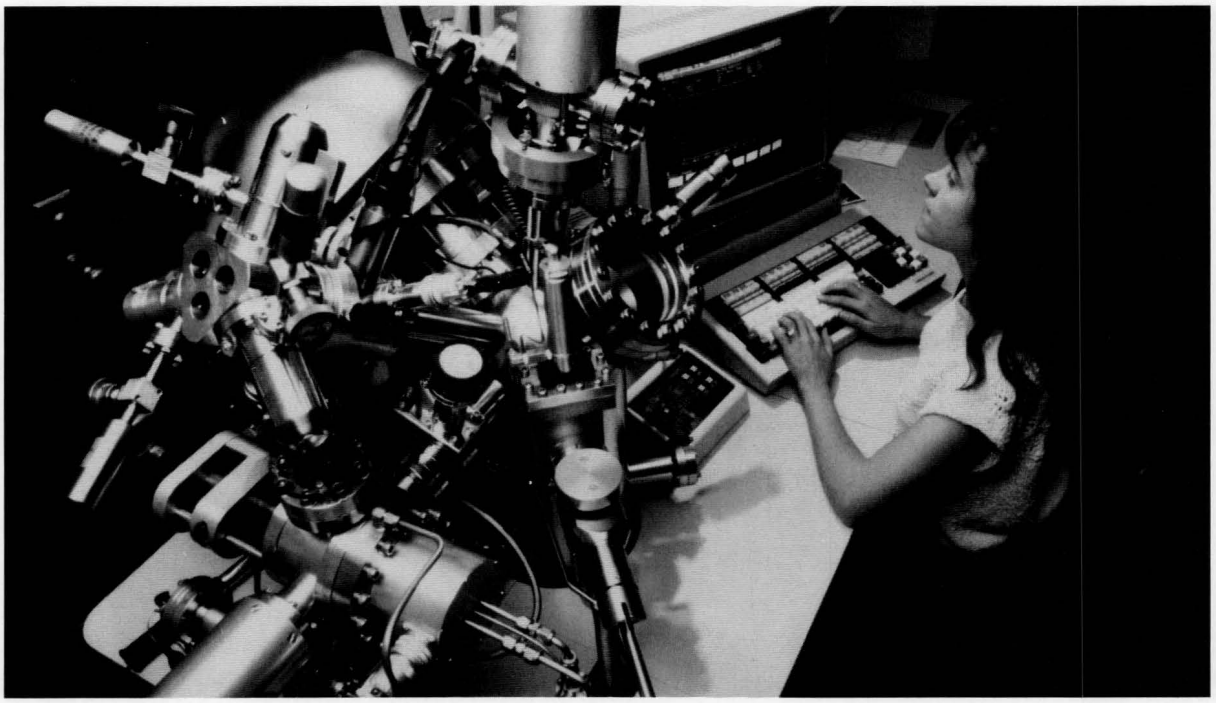
University of Pittsburgh



Graduate Studies in Chemical Engineering Purdue University

Faculty

..F. Albright, *Emeritus*
R.P. Andres
.M. Caruthers
K.C. Chao
V.N. Delgass
F.J. Doyle
R.E. Eckert
A.H. Emery
E.I. Franses
R.A. Greenkorn
H.L. Hampsch
R.E. Hannemann
R.N. Houze
O.P. Kessler
J.F. Pekny
N.A. Peppas
O. Ramkrishna
G.V. Reklaitis
R.G. Squires
C.G. Takoudis
. Talbot
G.T. Tsao
V. Venkatasubramanian
N.H.L. Wang
P.C. Wankat
J.M. Wiest



Research Areas

- Applied Mathematics
- Artificial Intelligence
- Biochemical Engineering
- Biomedical Engineering
- Catalysis and Reaction Engineering
- Colloids and Interfacial Engineering
- Process Operations and Design
- Environmental Science
- Materials and Microelectronics Processing
- Parallel Computing and Combinatorics
- Polymer Science and Engineering
- Process Control
- Separation Processes
- Surface Science and Engineering
- Thermodynamics and Statistical Mechanics
- Transport Phenomena

Degrees Offered

Master of Science
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Financial Assistance

Fellowships
Research Assistantships
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Graduate Studies
Purdue University
1283 Chemical Engineering Building
West Lafayette, Indiana 47907-1283

Phone: (317) 494-4057

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■ *Staff*

P. R. Bell (New South Wales)
I. T. Cameron (Imperial College)
C. A. Crosthwaite (Queensland)
D. D. Do (Queensland)
R. U. Edgehill (Cornell)
P. F. Greenfield (New South Wales)
T. Howes (Cambridge)
M. R. Johns (Massey)
P. L. Lee (Monash)
A. A. Krol (Queensland)
J.D. Litster (Queensland)
M. E. Mackay (Illinois)
D. A. Mitchell (Queensland)
R. B. Newell (Alberta)
S. Reid (Griffith)
V. Rudolph (Natal)
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E. T. White (Imperial College)
R. J. Wiles (Queensland)

■ *Adjunct Staff*

D. Barnes (Birmingham)
J. M. Burgess (Edinburgh)
W. W. Eckenfelder (Manhattan)
J. E. Hendry (Wisconsin)
G. W. Pace (MIT)
D. H. Randerson (New South Wales)

■ *Research Areas*

- Catalysis
- Fluidization
- Systems Analysis
- Computer Control
- Applied Mathematics
- Transport Phenomena
- Crystallization
- Polymer Processing
- Rheology
- Chemical Reactor Analysis
- Energy Resource Studies
- Oil Shale Processing
- Wastewater Treatment
- Landfill Practice
- Particle Mechanics
- Environmental Modeling
- Computational Fluid Dynamics
- Process Simulation
- Fermentation Systems
- Tissue Culture
- Enzyme Engineering
- Environmental Control
- Process Economics
- Mineral Processing
- Adsorption
- Membrane Processes
- Hybridoma Technology
- Numerical Analysis
- Large Scale Chromatography

■ *The Department*

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

■ *The University and the City*

The University is one of the largest in Australia with more than 22,000 students. Brisbane, with a population of about one million, enjoys a pleasant climate and attractive coasts which extend northward into the Great Barrier Reef.

■ *For further information write to*

Co-ordinator of Graduate Studies • Department of Chemical Engineering
The University of Queensland • Brisbane Qld 4072 Australia

Rensselaer

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

Advanced Study and Research Areas

- Advanced materials
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- Bioseparations
- Fluid-particle systems
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- High temperature kinetics
- Interfacial phenomena
- Microelectronics manufacturing
- Multiphase flow
- Polymer reaction engineering
- Process control and design
- Separation engineering
- Simultaneous diffusion and chemical reaction
- Thermodynamics
- Transport Processes

For full details write
Department Head
Department of Chemical Engineering
Rensselaer Polytechnic Institute
Troy, New York 12180-3590

The Faculty

Michael M. Abbott *Ph.D., Rensselaer*

Elmar R. Atwicker *Ph.D., Ohio State*

Georges Belfort *Ph.D., California—Irvine*

B. Wayne Bequette *Ph.D., Texas—Austin*

Henry R. Bungay, III *Ph.D., Syracuse*

Steven M. Cramer *Ph.D., Yale*

Arthur Fontijn *D.Sc., Amsterdam*

William N. Gill *Ph.D., Syracuse*

Martin E. Glicksman *Ph.D., Rensselaer*

Richard T. Lahey, Jr. *Ph.D., Stanford*

Howard Littman *Ph.D., Yale*

Morris H. Morgan, III *Ph.D., Rensselaer*

Charles Muckenfuss *Ph.D., Wisconsin*

E. Bruce Nauman *Ph.D., Leeds*

Joel L. Plawsky *D.Sc., M.I.T.*

Todd M. Przybycien *Ph.D., Cal. Tech*

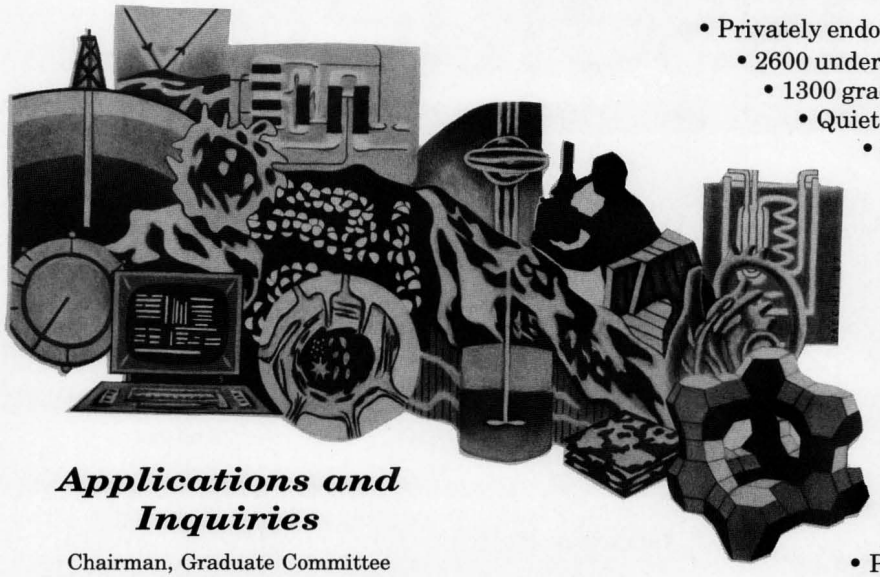
Hendrick C. Van Ness *D.Eng., Yale*

Peter C. Wayner, Jr. *Ph.D., Northwestern*

Robert H. Wentorf, Jr. *Ph.D., Wisconsin*

Rice University

Graduate Study in Chemical Engineering



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

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- Stipends and Tuition waivers for full-time students
- Special fellowships with high stipends for outstanding candidates

Faculty

- William W. Akers *(Michigan, 1950)*
- Constantine D. Armeniades *(Case Western Reserve, 1969)*
- Thomas A. Badgwell *(Texas, 1992)*
- 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)*
- George J. Hirasaki *(Rice, 1967)*
- Riki Kobayashi *(Michigan, 1951)*
- Larry V. McIntire *(Princeton, 1970)*
- Antonios G. Mikos *(Purdue, 1988)*
- Clarence A. Miller *(Minnesota, 1969)*
- Mark A. Robert *(Swiss Fed. Inst. of Technology, 1980)*
- Ka-Yiu San *(CalTech, 1984)*
- Jacqueline Shanks *(CalTech, 1989)*
- Kyriacos Zygourakis *(Minnesota, 1981)*

Research Interests

- Applied Mathematics
- Biochemical Engineering
- Biomedical Engineering
- Equilibrium Thermodynamic Properties
- Fluid Mechanics
- Interfacial Phenomena
- Kinetics and Catalysis
- Polymer Science
- Process Control
- Reaction Engineering
- Rheology
- Statistical Mechanics
- Transport Processes
- Transport Properties

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Professor Harvey J. Palmer, Chair
Department of Chemical Engineering
University of Rochester
Rochester, New York 14627
Phone: (716) 275-4042
Fax: (716) 442-6686

Faculty and Research Areas

S. H. CHEN, Ph.D. 1981, Minnesota
Polymer Science and Engineering, Transport Phenomena, Optical Materials

E. H. CHIMOWITZ, Ph.D. 1982, Connecticut
Critical Phenomena, Statistical Mechanics of Fluids, and Computer-Aided Design

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

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

J. C. FRIEDLY, Ph.D. 1965, California (Berkeley)
Process Dynamics, Control, Groundwater Transport

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

S. A. JENEKHE, Ph.D. 1985, Minnesota
Polymer Science and Engineering, Materials Chemistry, Optoelectronic and Photonic Materials and Devices

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

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

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

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

S. V. SOTIRCHOS, Ph.D. 1982, Houston
Reaction Engineering, Gas-Solid Reactions, Processing of Ceramic Materials

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

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Phase Equilibria
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Process Control
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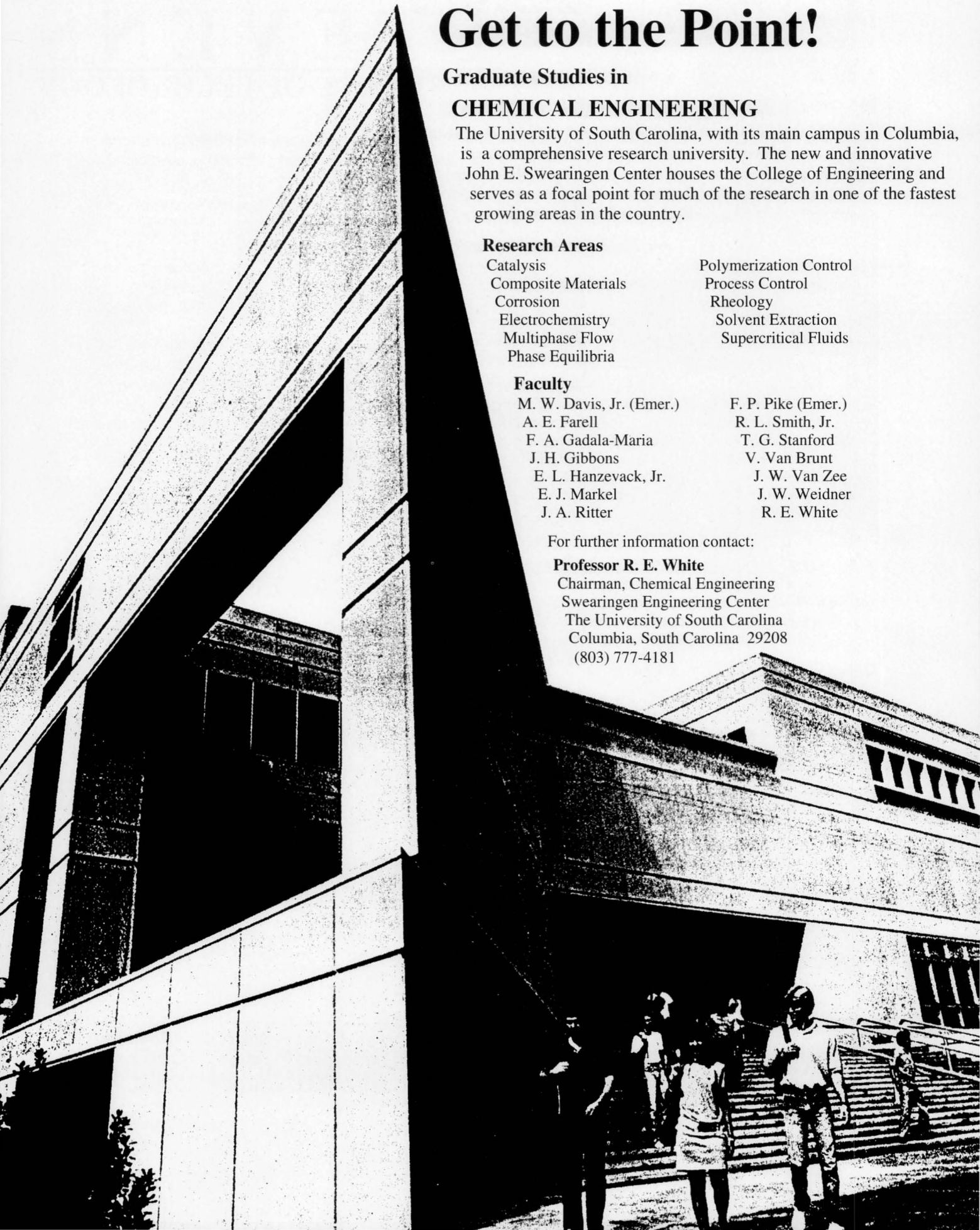
Solvent Extraction
Supercritical Fluids

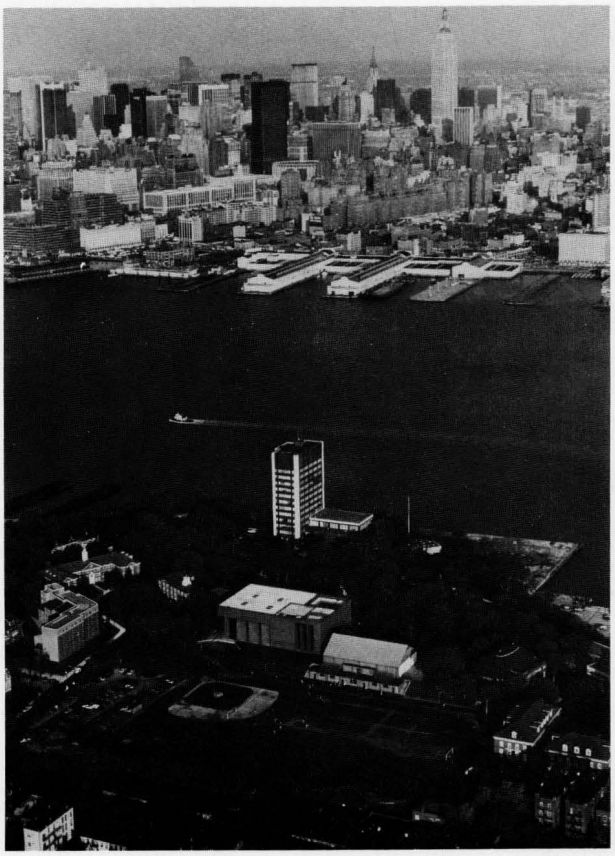
Faculty

M. W. Davis, Jr. (Emer.)
A. E. Farell
F. A. Gadala-Maria
J. H. Gibbons
E. L. Hanzevack, Jr.
E. J. Markel
J. A. Ritter
F. P. Pike (Emer.)
R. L. Smith, Jr.
T. G. Stanford
V. Van Brunt
J. W. Van Zee
J. W. Weidner
R. E. White

For further information contact:

Professor R. E. White
Chairman, Chemical Engineering
Swearingen Engineering Center
The University of South Carolina
Columbia, South Carolina 29208
(803) 777-4181





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C. G. Gogos (PhD, Princeton University)
D. M. Kalyon (PhD, McGill University)
S. Kovenklioglu (PhD, Stevens Institute of Technology)
S. Rivera (PhD, Colorado State University)
D. H. Sebastian (PhD, Stevens Institute of Technology)
H. Silla, Head, (PhD, Stevens Institute of Technology)

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Catalysis
Wastewater Treatment
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Stevens Institute of Technology
Hoboken, NJ 07030
201-216-5546

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201-216-5546

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Chemical Engineering at Texas

Research Interests

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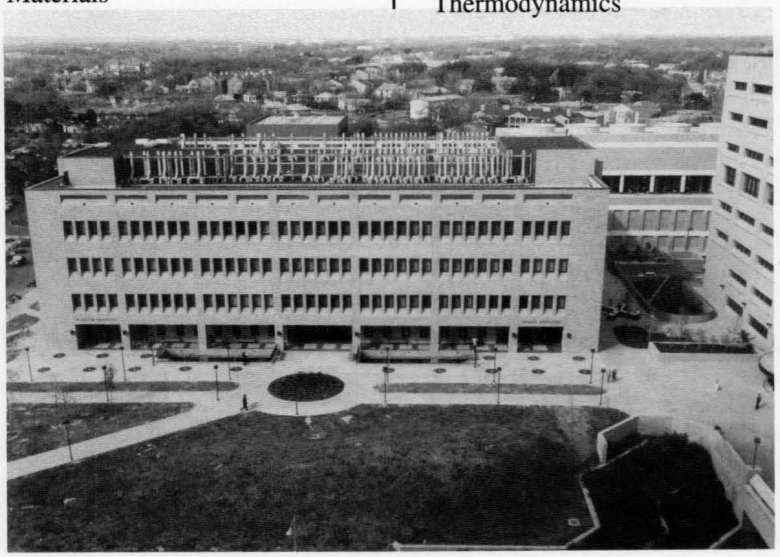
Aqueous Mass Transfer
Barrier Packaging
Biochemical & Biomedical Engineering
Biomaterials
Biosensors
Catalysis
Chemical Engineering Education
Chemical Reaction Kinetics
Chemical Vapor Deposition
Colloid & Surface Science
Combustion
Crystal Structure & Properties
Crystallization
Distillation
Electrochemistry
Electronic and Optical Materials

Research Interests (cont'd)

Enhanced Oil Recovery
Expert Systems
Fault Detection & Diagnosis
Flow of Suspensions
Fluid Mechanics
Heat Transfer
Laser Processing
Liquid Crystalline Polymers
Lithographic Materials
Materials Science
Membrane Science
Microelectronics Processing
Optimization
Plasma Processing
Polymer Blends
Polymer Processing
Polymer Synthesis
Polymer Thermodynamics
Process Dynamics & Control
Process Modeling & Simulation
Protein & Fermentation Engineering
Reaction Injection Molding
Separation Processes
Stack Gas Desulfurization
Statistical Thermodynamics
Superconductivity
Supercritical Fluid Science
Surface Science
Thermodynamics



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

Faculty

Joel W. Barlow
Wisconsin
Roger T. Bonnecaze
Caltech
James R. Brock
Wisconsin
Thomas F. Edgar
Princeton
John G. Ekerdt
Berkeley
James R. Fair
Texas
George Georgiou
Cornell
Adam Heller
Hebrew (Jerusalem)
David M. Himmelblau
Washington
Jeffrey A. Hubbell
Rice
Keith P. Johnston
Illinois
William J. Koros
Texas
Douglas R. Lloyd
Waterloo
John J. McKetta
Michigan
C. Buddie Mullins
Caltech
Donald R. Paul
Wisconsin
Robert P. Popovich
Washington
Ilya Prigogine
Brussels
Howard F. Rase
Wisconsin
James B. Rawlings
Wisconsin
Gary T. Rochelle
Berkeley
Isaac C. Sanchez
Delaware
Robert S. Schechter
Minnesota
Hugo Steinfink
Polytechnic (New York)
James E. Stice
Illinois Tech
Isaac Trachtenberg
Louisiana State
C. Grant Willson
Berkeley
Eugene H. Wissler
Minnesota

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RESEARCH AREAS

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- Process Control
- Separations
- Thermodynamics

R. W. Flumerfelt, Head, Ph.D.
Northwestern, 1965
Fluid mechanics, interfacial phenomena

A. Akgerman, Ph.D.
Virginia, 1971
Reaction engineering, waste treatment

R. G. Anthony, Ph.D.
Texas, 1966
Catalysis, reaction engineering

A. J. Appleby, Ph.D.
Cambridge (UK), 1965
Electrochemistry

D. B. Bukur, Ph.D.
Minnesota, 1974
Reaction engineering, math methods

J. A. Bullin, Ph.D.
Houston, 1972
Gas sweetening, asphalt characterization

B. E. Dale, Ph.D.
Purdue, 1979
Biochemical engineering

R. Darby, Ph.D.
Rice, 1962
Rheology, polymers

R. R. Davidson, Ph.D.
Texas A&M, 1962
Methanol fuel, asphalt characterization

L. D. Durbin, Ph.D.
Rice, 1961
Process control

P. T. Eubank, Ph.D.
Northwestern, 1961
Thermodynamics

A. M . Gadalla, Ph.D.
Sheffield (UK), 1964
Ceramics, materials science

C. J. Glover, Ph.D.
Rice, 1974
Polymer solutions

K. R. Hall, Ph.D.
Oklahoma, 1967
Thermodynamics

D. T. Hansen, Ph.D.
Minnesota, 1968
Biochemical engineering

C. D. Holland, Ph.D.
Texas A&M, 1953
Separation processes, distillation, unsteady-state processes

J. C. Holste, Ph.D.
Iowa State, 1973
Thermodynamics

M. T. Holtzapple, Ph.D.
Pennsylvania, 1981
Biochemical engineering

J. C. Liao, Ph.D.
Wisconsin, 1987
Biochemical engineering, metabolic engineering

M. Nikolaou, Ph.D.
UCLA, 1989
Process control, optimization and design

H. J. Ploehn, Ph.D.
Princeton, 1988
Colloidal and interfacial systems

A. T. Watson, Ph.D.
Cal Tech, 1979
Porous media, math modeling

For More Information

Graduate Admissions Office ▪ Department of Chemical Engineering
Texas A&M University
College Station, Texas 77843-3122 ▪ (409) 845-3361

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Ph.D., Northwestern University
Transport Phenomena, Mathematical Modeling and Numerical Methods

Ronald L. Fournier, Associate Professor
Ph.D., University of Toledo
Transport Phenomena, Thermodynamics, Mathematical Modeling and Biotechnology

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

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

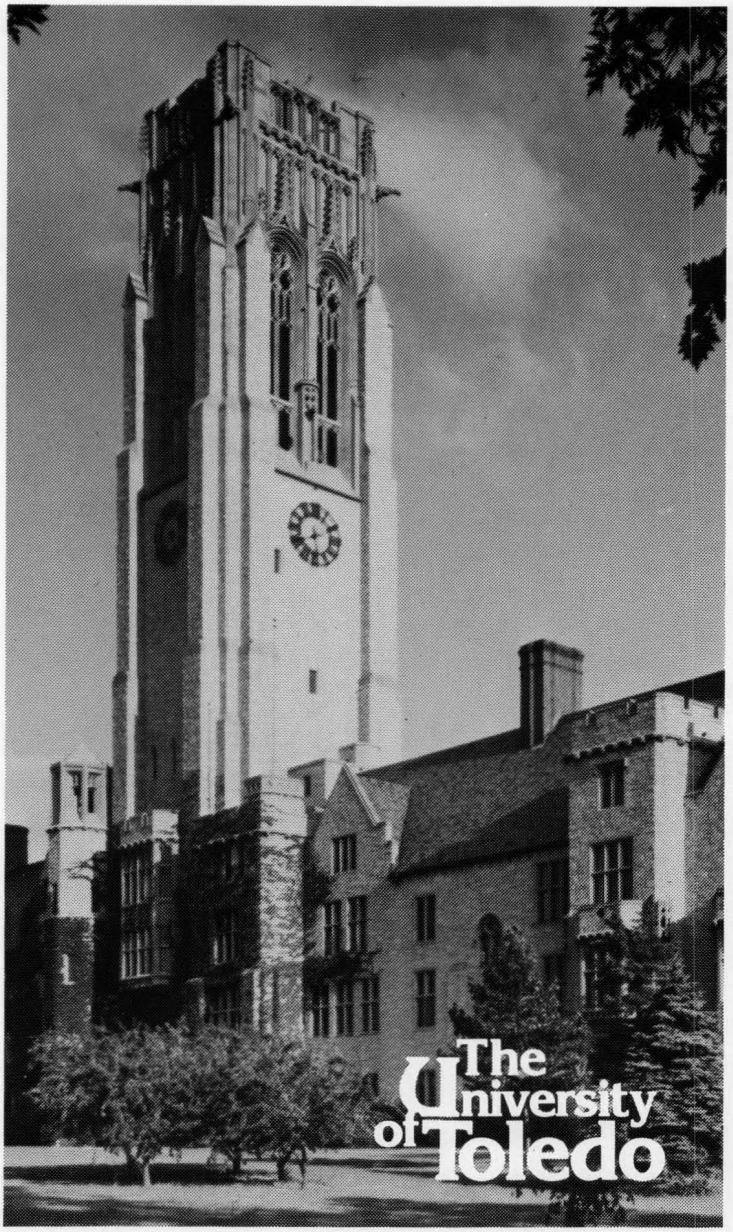
Richard M. Lemert, Assistant Professor
Ph.D., University of Texas at Austin
Thermodynamics and Supercritical Fluid Extraction

Bruce E. Poling, Professor, Chairman,
Ph.D., University of Illinois
Professor; Thermodynamics and Physical Properties

Sasidhar Varanasi, Associate Professor
PhD., State University of New York at Buffalo
Colloidal and Interfacial Phenomena, Enzyme Kinetics, Membrane Transport

For Details Contact:

Dr. B. E. Poling, Chairman
Department of Chemical Engineering
The University of Toledo
Toledo, OH 43606-3390
(419) 537-7736



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Engineering the World

The University of Tulsa

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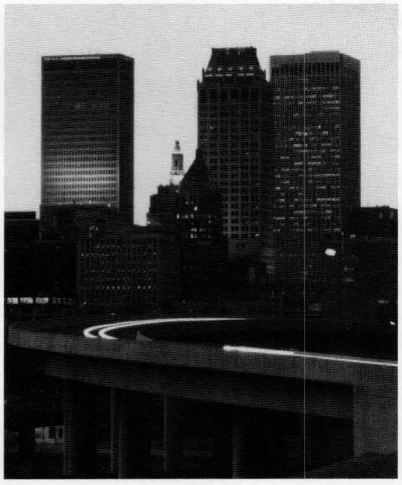
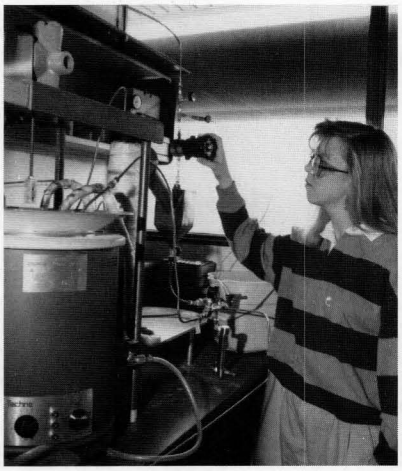


Tulsa, Oklahoma

Off-campus activities abound in Tulsa, one of the nation's most livable cities. Our temperate climate, with four distinct seasons, is perfect for year-round outdoor activities. With a metropolitan population of 450,000, the city of Tulsa affords opportunities for students to gain internship and work experience in its dynamic data processing, petroleum, medical, and financial industries. One can also enjoy world-class ballet, symphony and theatre performances, and exhibits in the cultural community. Annual events include Mayfest, Oktoberfest, the Chili Cook-off and Bluegrass Festival, the Tulsa Run, and the Jazz and Blues festivals.



Chemical Engineering at TU

TU enjoys a solid international reputation for expertise in the petroleum industry, and offers environmental and biochemical programs. The department places particular emphasis on experimental research, and is proud of its strong contact with industry.

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- Master of Engineering degree (a professional degree that can be completed in 18 months without a thesis)
- Special Master's degree for nonchemical engineering undergraduates

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The Faculty

M.A. Abraham • Reaction kinetics, catalysis, supercritical fluids
. Ariman • Particulate science and technology, multiphase separation processes
.L. Cerro • Capillary hydrodynamics, multiphase flows
.P. Hesketh • Combustion, incineration and pollution control
.D. Luks • Thermodynamics, phase equilibria
S. Manning • Industrial pollution control, surface processing of petroleum
.L. Sublette • Fermentation, biocatalysis, biological waste treatment
.E. Thompson • Oil and gas processing, computer-aided process design
.D. Wisecarver • Fluidization, bioreactor modeling, mass transfer and adsorption in porous solids

urther Information

raduate Program Director • Chemical Engineering Department
he University of Tulsa • 600 South College Avenue • Tulsa, Oklahoma 74104-3189
18) 631-2974 • Fax number: (918) 631-3268
-Mail: che_maa@vax1.utulsa.edu • Graduate School application: 1-800-882-4723

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Jamie Rudisill, B.S.ChE
Ph.D. 1992

Faculty and Research Areas

Giorgio Carta, *Ph.D., University of Delaware*
Absorption, adsorption, ion exchange, biological separations

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

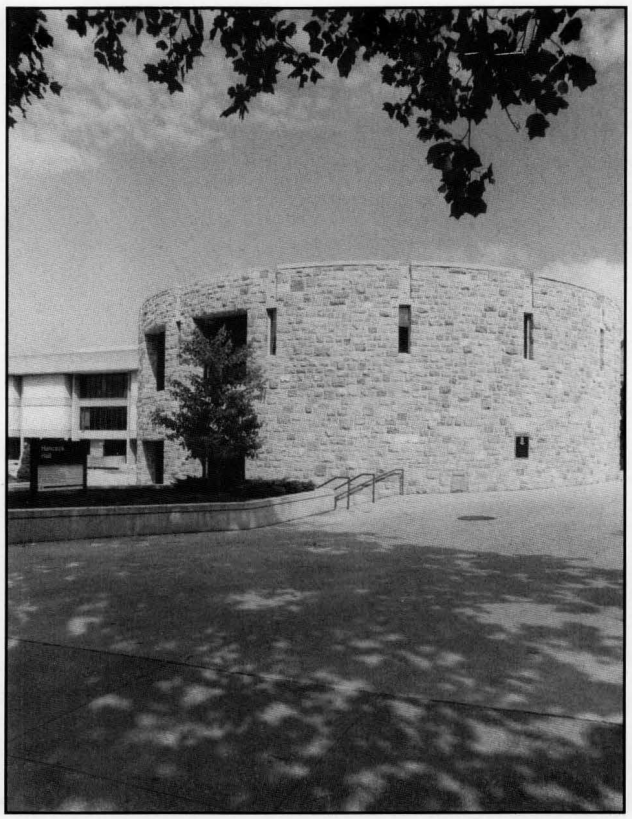
John P. O'Connell, *Ph.D., University of California, Berkeley*
Statistical thermodynamics with applications to physical and biological systems

To receive application materials and further information, please write to

Graduate Admissions Coordinator • Department of Chemical Engineering • Thornton Hall
University of Virginia • Charlottesville, VA 22903-2442 • Phone (804) 924-7778

Chemical Engineering

Virginia Tech



Hancock Hall, one of the most recent additions to the Virginia Tech campus, houses the Unit Operations Laboratory and many of the research facilities used in the processing of new materials.

For further information, contact the

Department of Chemical Engineering
Virginia Tech
133 Randolph Hall
Blacksburg, VA 24061

Telephone (703) 231-6631
FAX (703) 231-5022

FACULTY

Donald G. Baird
(Ph.D. University of Wisconsin)
The Harry C. Wyatt Professor
Polymer Processing and non-Newtonian Fluid Mechanics

William L. Conger
(Ph.D. University of Pennsylvania)
Professor and Department Head
Analysis of Coal Gasification Processes

David F. Cox
(Ph.D. University of Florida)
Associate Professor
Catalysis, Ultrahigh Vacuum Surface Science

Richey M. Davis
(Ph.D. Princeton University)
Assistant Professor
Physical Chemistry and Rheology of Colloids and Polymer Solutions

Kimberly E. Forsten
(Ph.D. University of Illinois)
Assistant Professor
Computational Bioengineering

Y. A. Liu
(Ph.D. Princeton University)
The Frank C. Vilbrandt Professor
Artificial Intelligence and Engineering Design

Eva Marand
(Ph.D. University of Massachusetts)
Assistant Professor
Transport through Polymer Membranes, Polymer Spectroscopy

Henry A. McGee Jr.
(Ph.D. Georgia Tech)
Professor
Molecular Engineering, Science Policy

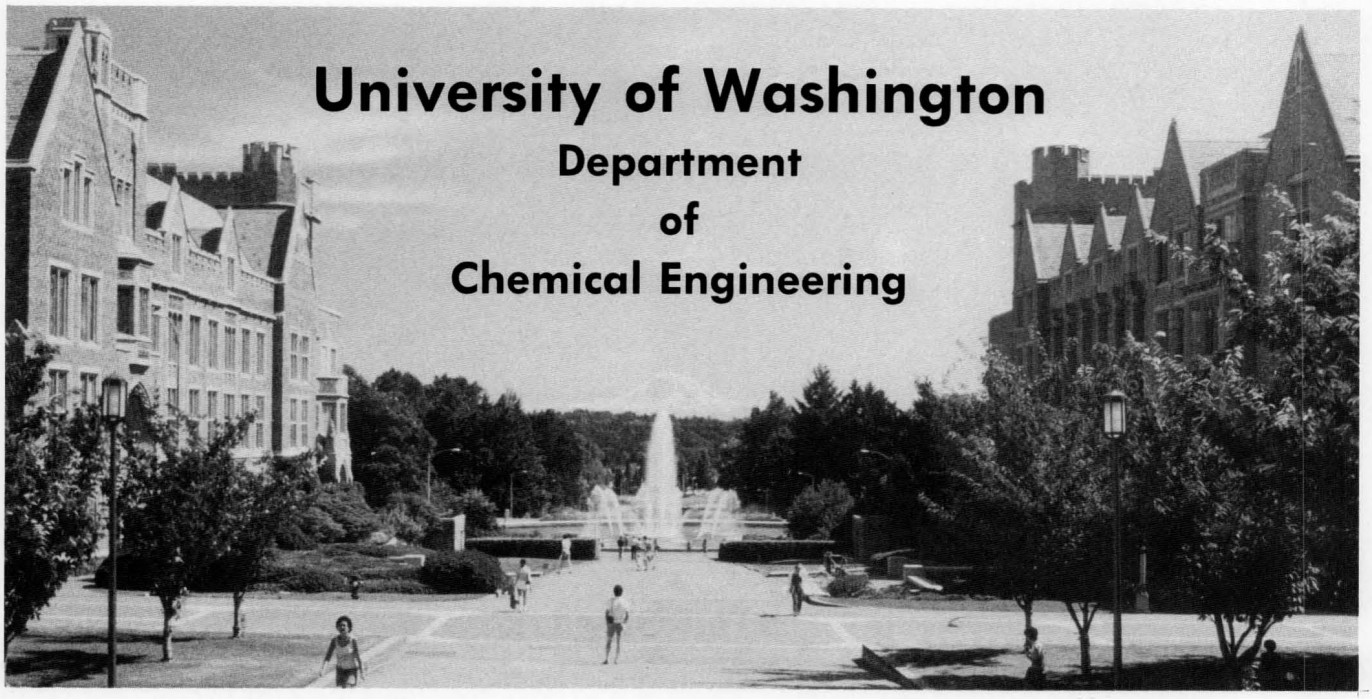
Donald L. Michelsen
(Ph.D. Cornell)
Associate Professor Emeritus
Waste Minimization/Treatment, Adsorption, and Indoor Air Quality

S. Ted Oyama
(Ph.D. Stanford University)
Associate Professor
Heterogeneous Catalysis and New Materials

Peter R. Rony
(Ph.D. University of California at Berkeley)
Professor
Instrumentation

William H. Velander
(Ph.D. Pennsylvania State University)
Associate Professor
Transgenic Livestock Bioreactors & Immunopurification of Therapeutics

Garth Wilkes
(Ph.D. University of Massachusetts)
The Fred W. Bull Professor
Structure-Property Behavior of Polymeric Materials



- Vigorous research program
- Excellent physical facilities
- Financial support for all full-time graduate students
- 65 graduate students from 30 universities and 20 states
- 15-20 students from foreign countries

Graduate students and faculty enjoy a fine *esprit de corps* in a stimulating and supportive research environment. Seattle, *The Emerald City,* provides outstanding cultural opportunities and unparalleled outdoor activities throughout the year. (Selected as the most livable city in the 1989 edition of *Places Rated Almanac.*)

Inquiries welcome. Please contact:

Graduate Admissions
Department of Chemical Engineering, BF-10
University of Washington
Seattle, Washington 98195

Phone: (206) 543-2250
Fax: (206) 543-3778

Chemical Engineering Faculty • Research Areas

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

Research Faculty

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

Adjunct and Joint Faculty Active in Department Research

G. Graham Allan, Ph.D., D.Sc., Glasgow	•	Fiber and Polymer Science
Richard R. Gustafson, Ph.D., Washington	•	Pulp and Paper
Allan S. Hoffman, Sc.D., MIT	•	Biomaterials in Medicine and Biotechnology
Thomas A. Horbett, Ph.D., Washington	•	Biomaterials; Peptide Drug Delivery
William T. McKean, Ph.D., Washington	•	Pulp and Paper Science
Buddy D. Ratner, Ph.D., Brooklyn Polytechnic	•	Biomaterials; Polymers; Surface Characterization

WASHINGTON STATE UNIVERSITY

Chemical Engineering Department

Here at Washington State University, we are proud of our graduate program, and of our students. The program has been growing quickly in size and quality, but is still small and informal.

For a department of this size, the range of faculty research interests is very broad. Students choose research projects of interest to them, then have the opportunity—and the responsibility—to make an individual contribution.

Through a combination of core courses and many electives, students can gain a thorough understanding of the basics of chemical engineering.

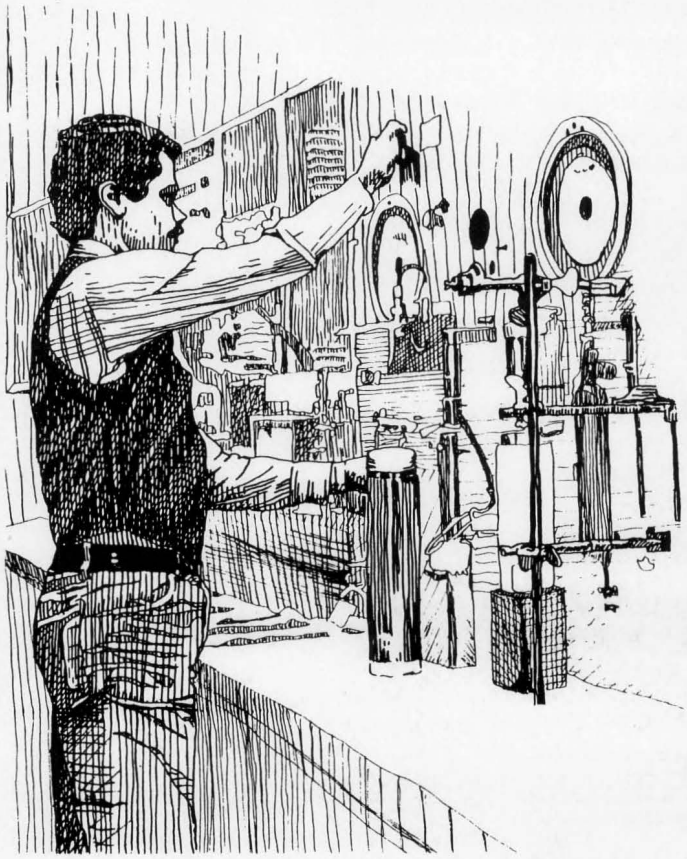
FACULTY AND RESEARCH INTERESTS

C. F. Ivory (Ph.D., Princeton): bioseparations, including electrophoresis, electrochromatography and field flow fractionation.

J. M. Lee (Ph.D., University of Kentucky): plant tissue cultivation, genetic engineering, enzymatic hydrolysis, mixing

K. C.Liddell (Ph.D., Iowa State University): semiconductor electrochemistry, reactions on fractal surfaces, separations, radioactive waste management

R. Mahalingam (Ph.D., University of Newcastle-upon-Tyne): multiphase systems, physical and chemical separations, particulate phoretic phenomena, electronic materials and polymers, synfuels and environment



J. N. Petersen (Ph.D., Iowa State University); adaptive 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 precursers, chemical reaction engineering

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

R. L. Zollars (Ph.D., University of Colorado); multiphase reactor design, polymer reactor design, colloidal phenomena, chemical vapor deposition reactor design

GRADUATE DEGREE PROGRAMS AT WSU

M.S. in Chemical Engineering

Twelve credits in graduate chemical engineering courses, nine credits in supporting courses, and a thesis are required.

Ph.D. in Chemical Engineering

Eighteen credits in graduate chemical engineering courses, sixteen credits in supporting courses, and a dissertation are required. Upon successful completion of the coursework and the Ph.D. preliminary examination, a student is admitted to candidacy for the degree. The dissertation must represent a significant original contribution to the research literature.

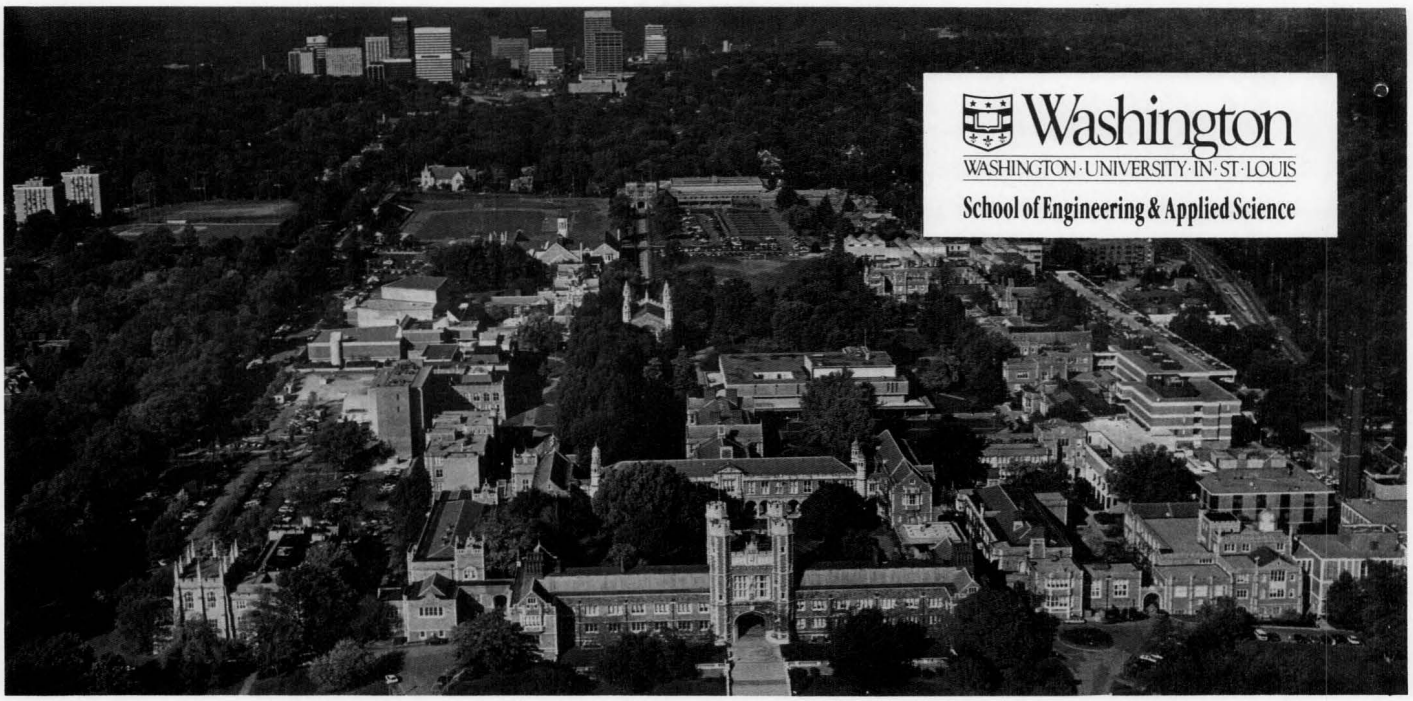
Conversion Program

Students with B.S. degrees in the physical or life sciences may apply for admission to the conversion program. Normally a small number of undergraduate courses must be taken in addition to the regular requirements for the M.S. or Ph.D.

FINANCIAL ASSISTANCE

Research or teaching assistantships, partial tuition waivers, and fellowships are available, and nearly all of our students receive financial assistance. Living costs are quite low.

WANT TO APPLY? Contact: Dr. C. F. Ivory, Graduate Coordinator, Department of Chemical Engineering, Washington State University, Pullman, WA 99164-2710
509/335-4332 or 509/335-7716

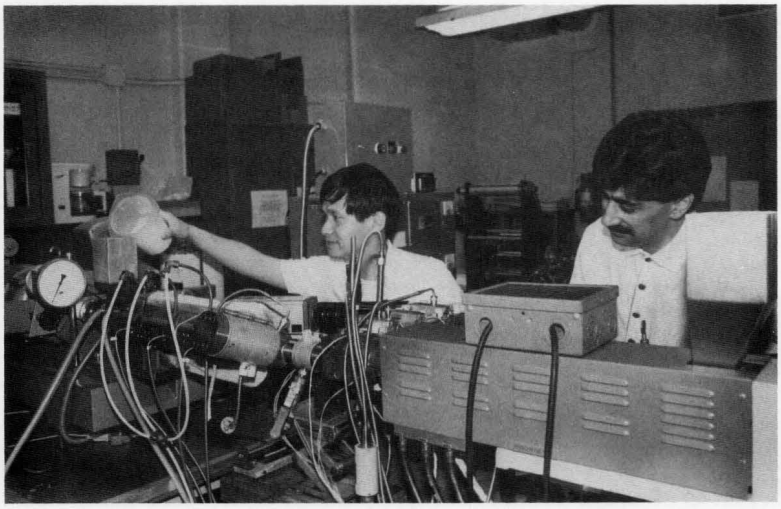


GRADUATE STUDY IN **CHEMICAL ENGINEERING**

MASTER'S AND DOCTORAL PROGRAMS

• *Faculty and Research Areas* •

M. P. Dudukovic	Chemical Reaction Engineering
J. T. Gleaves	Heterogeneous Catalysis, Surface Science, Microstructured Materials
B. Joseph	Process Control, Process Optimization, Expert Systems
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, Micro-encapsulation, Transport Phenomena
C. Thies	Biochemical Engineering, Microencapsulation
M. Underwood	Unit Operations, Process Safety, Polymer Processing



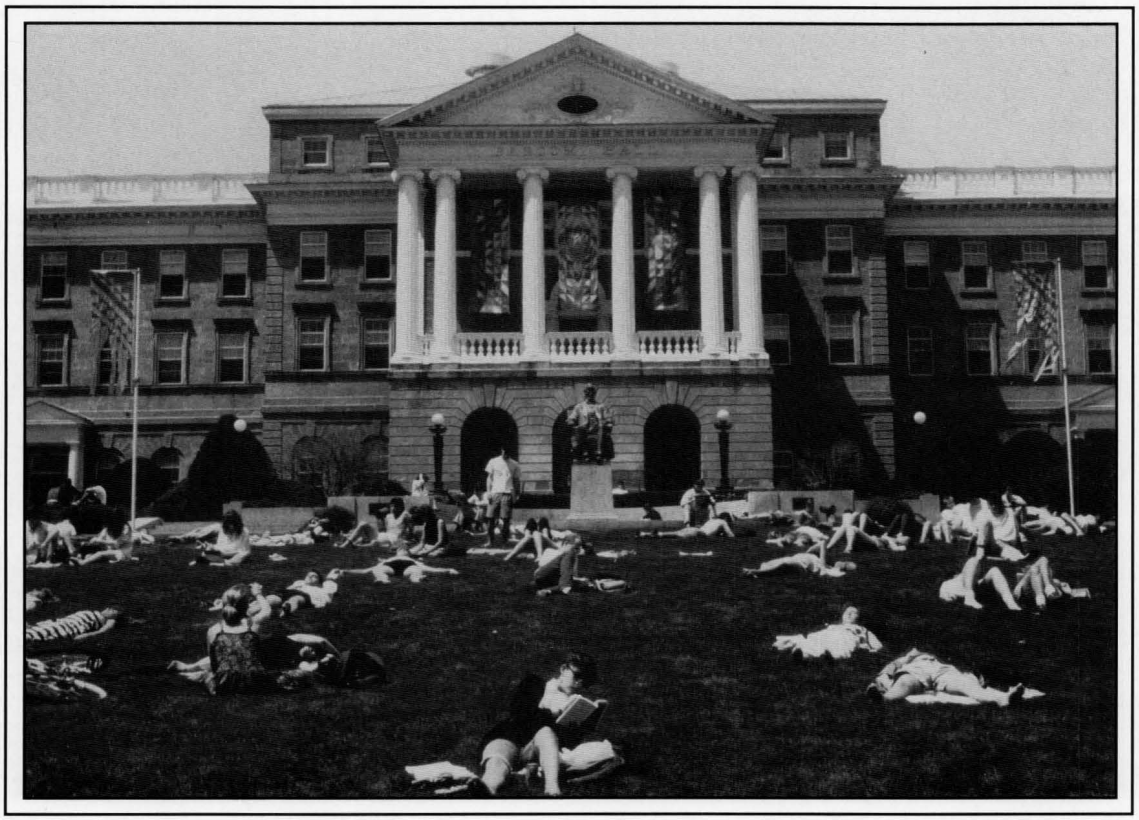
For Information Contact

Graduate Admissions Committee
Washington University
Department of Chemical Engineering
Campus Box 1198
One Brookings Drive
St. Louis, Missouri 63130-4899

Washington University encourages and gives full consideration to application for admission and financial aid without respect to sex, race, handicap, color, creed or national origin.

Wisconsin

A tradition of excellence in Chemical Engineering



Faculty Research Interests

Kevin L. Bray
High pressure solid-state chemistry, electronic properties of materials

Douglas C. Cameron
Biotechnology, metabolic engineering

Thomas W. Chapman
Electrochemical reaction engineering

Juan de Pablo
Molecular thermodynamics, statistical mechanics

James A. Dumesic (Chairman)
Kinetics and catalysis, surface chemistry

Michael D. Graham
Fluid mechanics, reaction-transport systems, applied and computational mathematics

Charles G. Hill, Jr.
Kinetics and catalysis, membrane separation processes, immobilized enzymes

Sangtae Kim
Fluid mechanics, applied mathematics, parallel computing

Daniel J. Klingenberg
Colloid science, transport phenomena

James A. Koutsky
Polymer science, adhesives, composites

Thomas F. Kuech
Semiconductor processing, solid-state and electronic materials, thin films

Stanley H. Langer
Kinetics, catalysis, electrochemistry, chromatography, hydrometallurgy

E. N. Lightfoot, Jr.
Mass transfer and separations processes, biochemical engineering

Regina M. Murphy
Biomedical engineering, applied immunology, protein-protein interactions

W. Harmon Ray
Process dynamics and control, reaction engineering, polymerization

Thatcher W. Root
Surface chemistry, catalysis, solid-state NMR

Dale F. Rudd
Process design and industrial development

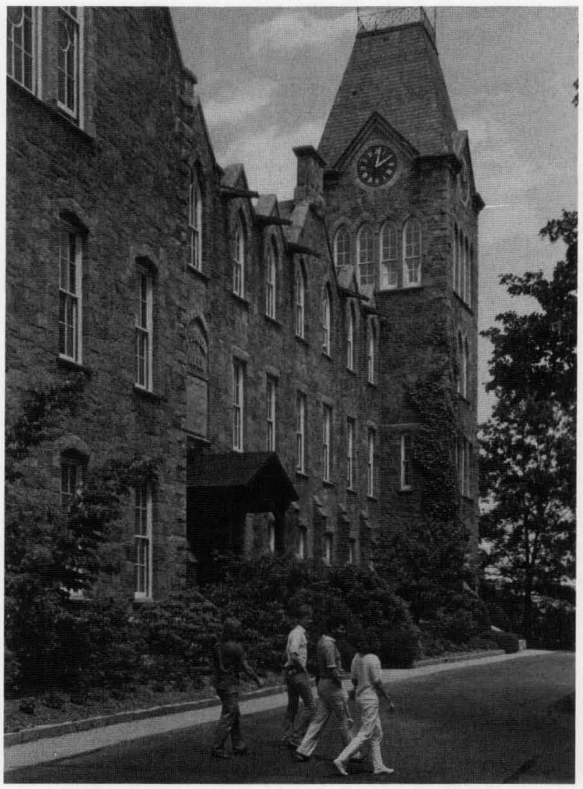
Warren E. Stewart
Reactor modeling, fractionation modeling, transport phenomena, applied mathematics

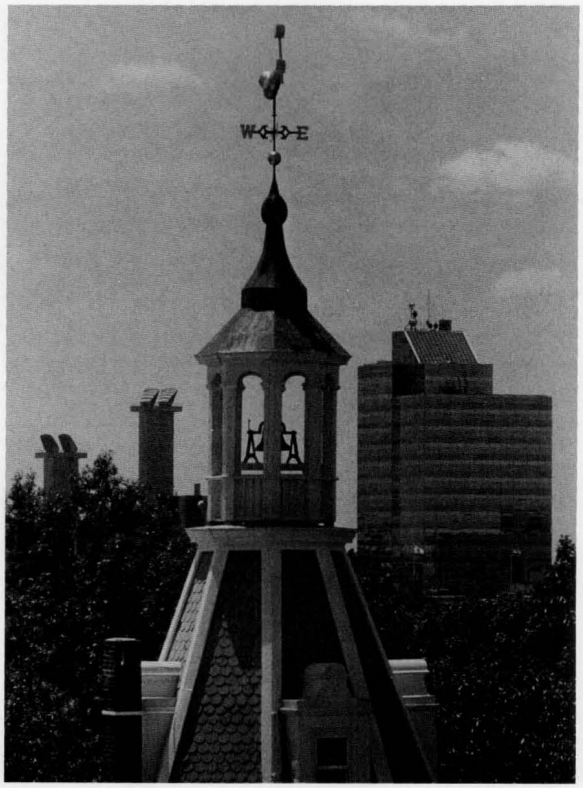
Ross E. Swaney
Process design, synthesis, modeling, and optimization

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

The Graduate Committee
Department of Chemical Engineering
University of Wisconsin–Madison
1415 Johnson Drive
Madison, Wisconsin 53706-1691

Graduate Studies in Chemical Engineering





Areas of Research:

Advanced Materials
- Carbon Filaments
- Inorganic Membranes
- Materials Processing in Space
- Molecular Sieve Zeolites

Biochemical Engineering
- Biopolymer Engineering
- Bioreactor Analysis
- Bioseparations

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

Environmental Engineering
- Aerosol Dynamics
- Nucleation and Phase Transitions
- Waste Reduction Technology

Faculty:

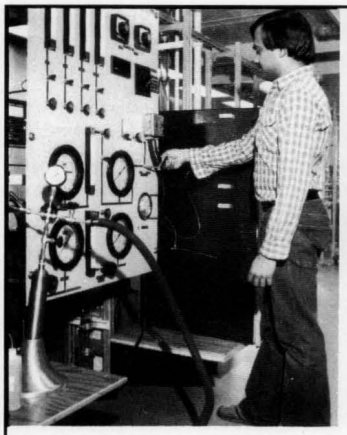
William M. Clark • *Ph.D., Rice*
David DiBiasio • *Ph.D., Purdue*
Anthony G. Dixon • *Ph.D., Edinburgh*
Yi Hua Ma • *Sc.D., MIT*
William R. Moser • *Ph.D., MIT*
James E. Rollings • *Ph.D., Purdue*
Albert Sacco, Jr. • *Ph.D., MIT*
Robert W. Thompson • *Ph.D., Iowa State*
Alvin H. Weiss • *Ph.D., Pennsylvania*
Barbara E. Wyslouzil • *Ph.D., CalTech*

The Central New England Area:
WPI is situated on a 62-acre hilltop site in a residential area of Worcester, Massachusetts, New England's second largest city and a leading cultural, educational, and entertainment center. It is a one-hour drive from Boston and only two hours from the beaches of Cape Cod and the ski slopes and hiking trails of Vermont and New Hampshire.

For further information on the M.S. and Ph.D. programs, contact:

Graduate Coordinator
Chemical Engineering Department
100 Institute Road
Worcester Polytechnic Institute
Worcester, MA 01609-2280

WORCESTER POLYTECHNIC INSTITUTE



Persons seeking admission, employment or access to programs of the University of Wyoming shall be considered without regard to race, color, national origin, sex, age, religion, policitical belief, handicap or veteran status.

UNIVERSITY OF WYOMING

Chemical Engineering

P. K. Agarwal	*coal combustion/gasification • fluidization • image analysis*
C. Y. Cha	*solid waste utilization • microwave reactors • gas clean-up*
D. O. Cooney	*mass transfer • scrubbers • air and water pollution*
H. A. Deans	*enhanced oil recovery • carbon dioxide flooding*
J. W. Glass	*environmental*
R. D. Gunn	*coal drying • active carbon • mathematical modeling*
H. W. Haynes	*catalysis • reaction kinetics • synthetic fuels*
M. A. Matthews	*transport properties • thermodynamics*
M. Merrill	*applications of magnetic resonance imaging*
H. F. Silver	*coal liquefaction • desulfurization*
J. G. Speight	*coal chemistry*

We offer exciting opportunities for research in many processing areas, especially energy related technology development. In recent years we have developed clean coal, solid waste utilization, and advance gas clean-up technologies up to bench scale levels. Currently we are working with industry to construct and operate pilot units of these technologies. This will provide excellent opportunities for students to obtain hands-on experience on industrial projects. Also, research has been conducted in the areas of kinetics, catalysis, adsorption, extraction, computer modeling, coal processing, and enhanced oil recovery.

The Western Coal Consortium has been established by the Chemical Engineering Department with western coal producers and utilities. The Western Coal Consortium and Enhanced Oil Recovery Institute and NSF/EPSCoR Program provide excellent financial aid packages to graduate students.

The University of Wyoming is located in Laramie, Wyoming at an elevation of 7200 feet. The town is surrounded by state and national parks which allow for beautiful year-round outdoor activities. The nearby Snowy Range mountains provide ideal sources of recreation for mountain and rock climbing, skiing, fishing, and hunting.

Graduates of any accredited chemical engineering program are eligible for admission, and the department offers both an M.S. and Ph.D. accredited program. Financial aid is available, and all recipients receive full fee waivers.

For more information contact

Dr. Chang-Yul Cha, Head • Department of Chemical Engineering • University of Wyoming
P. O. Box 3295 • Laramie, WY 82071-3295

YALE Department of Chemical Engineering

Douglas D. Frey, *Ph.D. Berkeley*

Gary L. Haller, *Ph.D. Northwestern*

Csaba G. Horváth, *Ph.D. Frankfurt*

James A. O'Brien, *Ph.D. Pennsylvania*

Lisa D. Pfefferle, *Ph.D. Pennsylvania*

Theodore W. Randolph, *Ph.D. Berkeley*

Daniel E. Rosner, *Ph.D. Princeton*

Robert S. Weber, *Ph.D. Stanford*

Adjunct Professors:

- **Leslie S. Ettre**
- **John P. Marano**

Lecturers:

- **Joseph J. Levitzky**
- **John Bett**
- **Jovan Boskovic**
- **Yehia Khalil**

Department of Chemical Engineering
Yale University
2159 Yale Station
New Haven, Ct 06520
Phone: (203) 432-2222
FAX: (203) 432-7232

Adsorption

Aggregation, Clustering

Biochemical Engineering

Catalysis

Chemical Reaction Engineering

Chemical Vapor Deposition

Chromatography

Combustion

Enzyme Technology

Fine Particle Technology

Heterogeneous Kinetics

Interfacial Phenomena

Molecular Beams

Multiphase Transport Phenomena

Separation Science and Technology

Statistical Thermodynamics

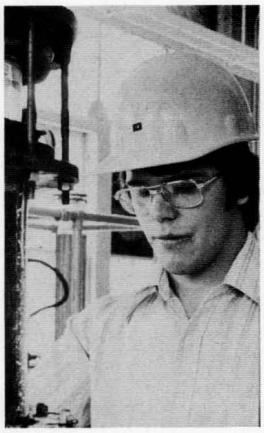
Supercritical Fluid Phenomena

BUCKNELL

BUCKNELL UNIVERSITY
Department of Chemical Engineering

MS PROGRAM

W. E. KING, JR., Chair
(PhD, University of Pennsylvania)
Biomedical engineering



J. CSERNICA
(PhD, M.I.T.)
Materials science, polymer structures/property relations

M. E. HANYAK, JR.
(PhD, University of Pennsylvania)
Computer-aided design, thermodynamics, applied software engineering

F. W. KOKO, JR.
(PhD, Lehigh University)
Optimization, fluid mechanics, direct digital control

J. E. MANEVAL
(PhD, University of California, Davis)
Multiphase transport processes, ion exchange, nuclear magnetic resonance imaging

J. M. POMMERSHEIM
(PhD, University of Pittsburgh)
Transport phenomena, mathematical modeling, cement hydration

M. J. PRINCE
(PhD, U. of California, Berkeley)
Biochemical engineering, interfacial phenomena

D. S. SCHUSTER
(PhD, West Virginia Univ.)
Fluidization, particulate systems, agglomerations

W. J. SNYDER
(PhD, Pennsylvania State U.)
Catalysis, polymerization, instrumentation

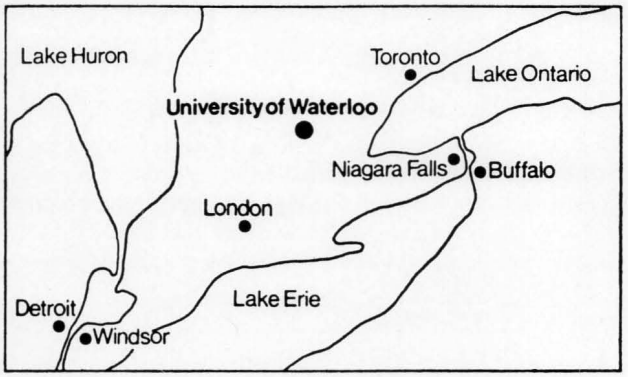
Bucknell is a small, private, highly selective university with strong programs in engineering, business, and the liberal arts. The Department is located in the newly renovated Charles A. Dana Engineering Building which provides ample facilities for both computational and experimental research. State-of-the-art computing for both research and course work and modern laboratory equipment are readily available. Graduate students have a unique opportunity to work very closely with a faculty research advisor.

Lewisburg, located in the center of Pennsylvania, provides the attraction of a rural setting while conveniently located within 200 miles of New York, Philadelphia, Washington, D.C., and Pittsburgh.

For further information, write or phone

Dr. William E. King, Jr., Chair
Department of Chemical Engineering
Bucknell University
Lewisburg, PA 17837
717-524-1114

UNIVERSITY OF WATERLOO



Canada's largest Chemical Engineering Department offers regular and co-operative M.A.Sc., Ph.D., and post-doctoral programs in:

- Biochemical and Food Engineering
- Industrial Biotechnology
- Chemical Kinetics, Catalysis, and Reactor Design
- Environmental and Pollution Control
- Extractive and Process Metallurgy
- Polymer Science and Engineering
- Mathematical Analysis, Statistics, and Control
- Transport Phenomena, Multiphase Flow
- Enhanced Oil Recovery
- Electrochemical Processes, Solids, Handling

Financial Aid: RA: $14,500/yr
TA: $5,000/yr (approximate)
Scholarships

G. L. Rempel, Ph.D. *(UBC)*, Chair; **P. L. Douglas,** PhD *(Waterloo)*, Associate Chair Graduate; **I. F. Macdonald,** PhD *(Wisconsin)*, Associate Chair Undergraduate; **W. A. Anderson,** PhD *(Waterloo)*; **H. Budman,** PhD *(Technion-Israel)*; **C. M. Burns,** PhD *(Polytech. Inst. Brooklyn)*; **J. J. Byerley,** PhD *(UBC)*; **I. Chatzis,** PhD *(Waterloo)*; **T. A. Duever**, PhD *(Waterloo)*; **F. A. L. Dullien**, PhD *(UBC)*; **T. Z. Fahidy**, PhD *(Illinois)*; **G. J. Farquhar**, PhD *(Wisconsin)*; **B. R. Glick,** PhD *(Waterloo)*; **R. Y. M. Huang,** PhD *(Toronto)*; **R. R. Hudgins**, PhD *(Princeton)*; **R. L. Legge,** PhD *(Waterloo)*; **M. Moo-Young,** PhD *(London)*; **F. T. T. Ng,** PhD *(UBC)*; **K. F. O'Driscoll,** PhD *(Princeton)*; **R. Pal,** PhD *(Waterloo)*; **A. Penlidis,** PhD *(McMaster)*; **M. D. Pritzker**, *(V.P.I.)*; **P. M. Reilly,**PhD *(London)*; **C. W. Robinson,** PhD *(Berkeley)*; **A. Rudin,** PhD *(Northwestern)*; **J. M. Scharer,** PhD *(Pennsylvania)*; **D. S. Scott,** PhD *(Illinois)*; **P. L. Silveston,** Dr.Ing. *(Munich)*; **C. Tzoganakis,** PhD *(McMaster)*; **J. R. Wynnyckyj,** PhD *(Toronto)*

To apply or request information, send e-mail to
gradapp@cape.uwaterloo.ca
or contact
The Associate Chair (Graduate Studies)
Department of Chemical Engineering • University of Waterloo
Waterloo, Ontario, Canada N2L 3G1
Phone: 519-885-1211 • FAX: 519-746-4979

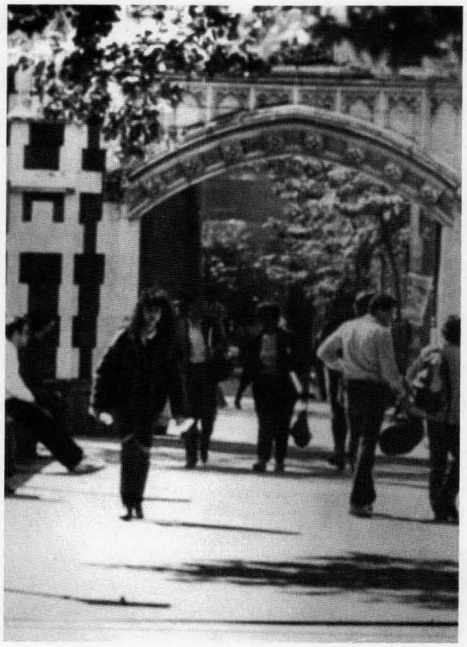
The University of California, San Diego

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

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

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

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



THE CITY COLLEGE

of The City University of New York

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

FACULTY

A. Acrivos
R. Graff
K. Guinn
L. Isaacs
C. Maldarelli
R. Mauri
R. Pfeffer
I. Rinard
D. Rumschitzki
R. Shinnar
C. Steiner
G. Tardos
H. Weinstein

RESEARCH AREAS

Fluid Mechanics
Coal Liquefaction
Materials
Colloid & Interfacial Phenomena
Composite Materials, Suspensions, Porous Media
Hydrodynamic Stability
Low Reynolds Number Hydrodynamics
Process Simulation and Control
Critical Separations
Process Systems Engineering and Design
Reaction Engineering
Industrial Economics
Polymer Science
Air Pollution
Fluidization
Biomembranes
Bioengineering

For applications for admission, assistantships and fellowships, please write to
D. Rumschitzki • Department of Chemical Engineering
City College of New York • Convent Ave. at 140th Street • New York, NY 10031

University of Idaho

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

FACULTY

W. ADMASSU	*Synthetic Membranes for Gas Separations, Biochemical Engineering with Environmental Applications*
T. E. CARLESON	*Mass Transfer Enhancement, Chemical Reprocessing of Nuclear Wastes, Bioseparation*
D. C. DROWN	*Process Design, Computer Application Modeling, Process Economics and Optimization with Emphasis on Food Processing*
L. L. EDWARDS	*Computer Aided Process Design, Systems Analysis, Pulp/Paper Engineering, Numerical Methods and Optimization*
D. S. HOFFMAN	*Alternative Fuels, Process Analysis and Design*
M. L. JACKSON	*Mass Transfer in Biological Systems, Particulate Control Technology*
R. A. KORUS	*Polymers, Biochemical Engineering*
J. Y. PARK	*Chemical Reaction Analysis and Catalysis, Laboratory Reactor Development, Thermal Plasma Systems*
J. J. SCHELDORF	*Heat Transfer, Thermodynamics*
M. VON BRAUN	*Hazardous Waste Site Analysis, Computer Mapping*

The department has a highly active research program covering a wide range of interests. The northern Idaho region offers a year-round complement of outdoor activities including hiking, white water rafting, skiing, and camping.

A wide range of fellowships and assistantships is available.

FOR FURTHER INFORMATION AND APPLICATION WRITE

Graduate Advisor
Chemical Engineering Department
University of Idaho
Moscow, Idaho 83843

Imperial College of Science, Technology and Medicine

University of London

Department of Chemical Engineering and Chemical Technology

Imperial College, one of the constituent colleges of the University of London, was rated top of a recent survey of research in Great Britain and best in Europe for engineering in an independent survey of European Universities carried out by the French newspaper *Libération.* In both exercises the Department of Chemical Engineering gained the maximum possible rating. The College is located in central London in an area of museums, parks, and galleries.

Research in the Department ranges from technological studies of processes and equipment through to fundamental scientific study of the underlying physical and chemical phenomena. Excellent facilities are available for study towards Masters degrees (M.Sc., one year) and doctorates (Ph.D., three years).

Current Fields of Research are

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

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

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

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

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

JAMES SCOTT SHAFFER
(Ph.D., Ch.E., California, Berkeley, 1993) • Interfacial phenomena in polymeric composites; rheology of confined polymeric materials

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

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

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Chairman, Graduate Committee
Department of Chemical Engineering
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Buffalo, New York 14260

Acknowledgment

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acknowledges and thanks
the 155 chemical engineering departments which
contributed to our support in 1993 through their bulk subscriptions.

We also wish to thank
the 129 departments which have
announced their graduate programs in this issue.

THE UNIVERSITY OF BRITISH COLUMBIA

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Inquiries should be addressed to:

Graduate Advisor
Department of Chemical Engineering
THE UNIVERSITY OF BRITISH COLUMBIA
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AUTHOR GUIDELINES

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

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

• Specific suggestions on preparing papers •

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

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

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