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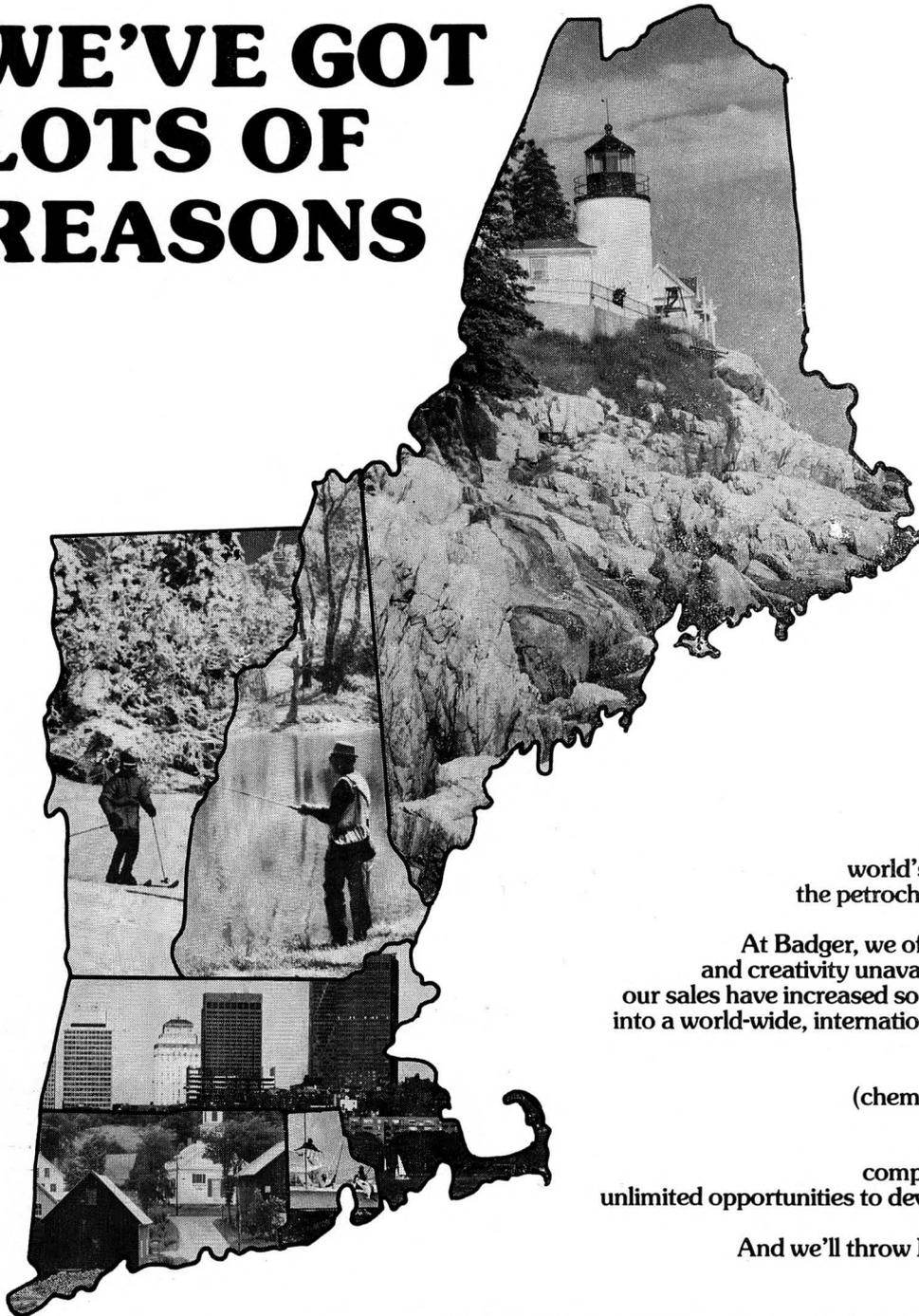
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# Chemical Engineering Education

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## In Memorium

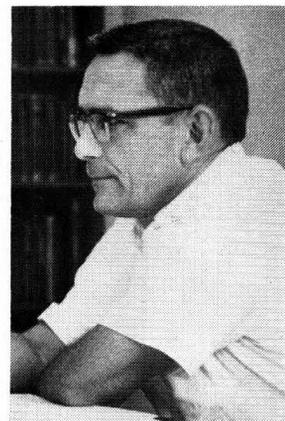
### *C. E. Littlejohn*

A. J. PERNA

*New Jersey Institute of Technology  
Newark, New Jersey 07102*

During the last week of May, 1975 many of us associated with Chemical Engineering were stunned and saddened with the announcement of the death of C. E. Littlejohn. To those of us who were aware of Charlie's condition, the news came as no great surprise but still left us numb with grief and disappointment. He is survived by his wife Doris and two daughters.

C. E. Littlejohn, Charlie or Doc Charlie as he was known to his colleagues and students, was born on September 28, 1918 in Spartanburg, S. C. His primary education was in the main undertaken at various schools in the South. He received his B. S. in Chemical Engineering from Clemson College in 1940; his M. S. from North Carolina State in 1941 and his Ph.D. from Virginia Polytechnic Institute in 1952. His professional activities include Chairman of the Western South Carolina Section of AIChE, Faculty Advisor to the Student AIChE Chapter, Member of AIChE-ECPD Accreditation Committee, Chairman of the Chemical Engineering Division of ASEE, and Chairman of the Publication Board of CEE. He was co-author of a Chemical Engineering sophomore level text, listed in Who's Who in the U.S., and selected as Man of the Year of the Western South Carolina Section of AIChE in 1970. Charlie joined the staff of the Chemical Engineering Department at Clemson as an Assistant Professor in 1947 and became Department Chairman in 1956. During this period the departmental staff consisted of Charlie and one other member with very little facilities of its own. However, from the students' point of view this was a positive feature since in meant Charlie taught many of the courses. He was an excellent teacher genuinely concerned with student problems and educational development. He set high standards in his courses but had the rare ability to transmit a keen sense of pride and professionalism to his students. (In fact, who can forget his lab grading system of



blue pencil for technical errors and red pencil for grammar mistakes).

In 1960 the department initiated its M.S. program followed by a Ph.D. program in 1962. In terms of educational philosophy Charlie's belief was that both the undergraduate and graduate training process should reflect an awareness of the industrial sector's needs. One of his quotes associated with the graduate program, during its initial growth stage, was the principle that, "A Differential Equation Never Built a Distillation Column." A belief that research should be used to enhance the expertise of an individual faculty member and ultimately this expertise be useful to the students in their educational development was impressed on his staff.

Insofar as his students were concerned, Charlie took an active interest in their careers and accomplishments. He was always available to both students and industrial representatives for advice, counseling and recommendations concerning career choices. The mark of esteem and affection he was held in is exemplified by the initiation this year of the C. E. Littlejohn Scholarship Fund initiated by industrial representatives who knew him.

Wherever any of "Charlie's Boys" (as his former students liked to refer to themselves) are, each one carries a favorite story or image of Doc Charlie from their own experiences. For myself, the picture I'll always associate with Charlie involves when our paths would cross at the AIChE Annual Meetings and we would get into long discussions on many topics and in my long winded way I would start a discourse on some chemical engineering educational related topic whereupon he would wait until I had finished and with a smile on his face he would properly admonish me with the introductory phrase, "Now, Angie . . .". Charlie, we are going to miss you!

**Editor's Note:** CEE also mourns the loss of our Publication Board Chairman. He has been succeeded by Prof. William Corcoran of California Institute of Technology.

## A LETTER TO CHEMICAL ENGINEERING SENIORS

As a senior you may be asking some questions about graduate school. In this issue CEE attempts to assist you in finding answers to them.

### *Should you go to graduate school?*

Through the papers in this special graduate education issue, *Chemical Engineering Education* invites you to consider graduate school as an opportunity to further your professional development. We believe that you will find that graduate work is an exciting and intellectually satisfying experience. We also feel that graduate study can provide you with insurance against the increasing danger of technical obsolescence. Furthermore, we believe that graduate research work under the guidance of an inspiring and interested faculty member will be important in your growth toward confidence, independence, and maturity.

### *What is taught in graduate school?*

In order to familiarize you with the content of some of the areas of graduate chemical engineering, we are continuing the practice of featuring articles on graduate courses as they are taught by scholars at various universities. Previous issues included articles on applied mathematics, transport phenomena, reactor design, fluid dynamics, particulate systems, optimal control, diffusional operations, computer aided design, statistical analysis, catalysis and kinetics, thermodynamics and certain specialized areas such as air pollution, biomedical and biochemical engineering. We strongly suggest that you supplement your reading of this issue by also reading the articles published in previous years. If your department chairman or professors cannot supply you with the latter, we would be pleased to do so at no charge. But before you read the articles in these issues we wish to point out that (1) there is some variation in course content and course organization at different schools, (2) there are many areas of chemical engineering that we have not been able to cover, and

(3) the professors who have written these articles are not the only authorities in these fields nor are their departments the only ones that emphasize that particular area of study.

### *Where should you go to graduate school?*

It is common for a student to broaden himself by doing graduate work at an institution other than the one from which he receives his bachelor's degree. Fortunately there are many very fine chemical engineering departments and each of these has its own "personality" with special emphases and distinctive strengths. For example, in choosing a graduate school you might first consider which school is most suitable for your own future plans to teach or to go into industry. If you have a specific research project in mind, you might want to attend a university which emphasizes that area and where a prominent specialist is a member of the faculty. On the other hand if you are unsure of your field of research, you might consider a department that has a large faculty with widely diversified interests so as to ensure for yourself a wide choice of projects. Then again you might prefer the atmosphere of a department with a small enrollment of graduate students. In any case, we suggest that you begin by writing the schools that have provided information on their graduate programs in the back of this issue. You will probably also wish to seek advice from members of the faculty at your own school.

But wherever you decide to go, we suggest that you explore the possibility of continuing your education in graduate school.

Sincerely,

RAY FAHIEN, Editor CEE  
University of Florida  
Gainesville, Florida

# MODERN THERMODYNAMICS

GIANNI ASTARITA

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Universita di Napoli, Naples, Italy.*

**I**N THE FALL Semester of both 1973 and 1974, a somewhat non-traditional course in Thermodynamics was given within the graduate program at the Chemical Engineering Department of the University of Delaware. The philosophy, scope and possible future evolution of this course are discussed in this report.

The teaching of Thermodynamics, at both the graduate and undergraduate level, in ChE departments is traditionally rather separated from the mainstream of the research and teaching activity of the department as a whole. Thermodynamics is often viewed as a self-contained subject, knowledge of which allows solving such important but rather traditional problems as energy balances, power cycles, and physical and chemical equilibria. This subject matter is what will be referred to in the following as classical thermodynamics.

An analysis of the scope of classical thermodynamics immediately shows that, as far as energy balances are concerned, only the first law is involved; for power cycles, the only materials considered are one-component ideal fluids suffering at the most complex a phase change; and for

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Gianni Astarita has received his M.Ch.E. at Delaware and his Ph.D. at the University of Naples. He is Professor of Chemical Engineering and Director of the Institute of Chemical Engineering Fundamentals at the University of Naples, and has a part-time appointment at the University of Delaware. He has research interests in Transport Phenomena, Rheology and Thermodynamics. He is the Italian Editor for Chemical Engineering Science, and has been the President of the Italian Society of Rheology in 1973-75. He is the author of "Mass Transfer with Chemical Reaction," Elsevier 1967, of "An Introduction to Non-linear Continuum Thermodynamics," spa Ed. Chimica 1975, and coauthor of "Principles of non-Newtonian Fluid Mechanics," McGraw-Hill 1974.

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## ACKNOWLEDGEMENTS

Prof. Hellinckx and Dr. Mewis of the Catholic University of Leuven are to be thanked for offering me in 1972 the first opportunity of teaching RT to ChE students. Prof. Metzner has been always very encouraging and has given all his personal support to this course. C. J. S. Petrie and S. I. Sandler gave valuable suggestions. H. B. Hopfenberg has offered useful comments. Finally, my whole approach to thermodynamic thinking has been greatly influenced by my work with Prof. Marrucci and Dr. Sarti.

physical and chemical equilibria, no transformation at all is involved, but only equilibrium states. With these limitations, the powerfulness of the second law as a starting point for a theory of irreversibility of processes undergone by possibly very complex materials is left entirely unexplored; and consequently the core of ChE, say the theory of transport phenomena, chemical kinetics, process dynamics, and so on is developed almost without regard to its relationship with thermodynamics.

The course given at Delaware has been based on the idea that there is no reason why thermodynamics could not, and indeed should not, have a central role in ChE methodology. An effort has thus been made towards the application of thermodynamic thinking to non-traditional areas, and particularly to those where strong research interests exist in the department. This seems a logical requirement for a graduate course in thermodynamics if it wants to have an educational value over and above its purely tutorial content. This also poses the question of the role of thermodynamics in ChE, which will be discussed in some detail in the "future evolution" section below.

## PHILOSOPHY

The syllabus of the course given at Delaware in 1973 and 1974 is summarized in Table I. Particular emphasis was placed on the logical analysis

of the fundamental structure of thermodynamic methodology (see sections B, C1, and D), and applications were restricted to a subject of prevailing interest in the research program of the department, namely, polymer deformation and flow (section C2), and to the traditional subject of equilibria (section E).

The philosophy of the course is non traditional in three aspects. First of all, since frictional heating and dissipation in flowing polymers wants to be analyzed, a thermodynamic theory of **irreversible** phenomena, with no Onsager-type re-

**TABLE I**  
**Syllabus of the Course**

Section A.	Mathematical preliminaries.	5 hours
Section B.	Classical continuum thermodynamics.	13 hours
	B1. Isothermal systems.	4 hours
	B2. Non-isothermal systems.	5 hours
	B3. Classical theories (Ideal fluids, Viscous fluids, Elastic solids).	4 hours
Section C.	Materials with memory.	7 hours
	C1. Thermodynamics and memory.	4 hours
	C2. Thermomechanics of polymers.	3 hours
Section D.	Axiomatic foundation for classical equilibria.	7 hours
	D1. Internal state variables, Affinity, Equilibrium.	3 hours
	D2. Axiomatic stoichiometry.	3 hours
Section E.	Classical equilibria.	8 hours
	E1. Phase equilibria.	4 hours
	E2. Chemical equilibria.	4 hours

striction to linearity, has to be considered explicitly. Second, since the phenomena considered involve systems the state of which is in general different at different points in space (suffice it to consider that temperature may be non-uniform, see section B2), a **field** theory of thermodynamics is required. Finally, since the peculiar thermodynamic behavior of polymers is related to their complex response to mechanical and thermal stimuli, and following a trend which has become progressively stronger in the theory of transport phenomena, particular emphasis has been placed on the role of **constitutive assumptions** in a thermodynamic theory.

#### **RATIONAL THERMODYNAMICS**

**A** FIELD THEORY of thermodynamics applicable to irreversible phenomena in materials with complex constitutive equations has been developed in the last ten years mainly by Coleman, Day, Gurtin, Mueller, Owen, Truesdell and Williams; it is usually referred to as Rational

Thermodynamics (RT). A critical review of the relevance of RT in chemical engineering is available [1]. The material summarized in Table I has been taught following the methodology of RT.

Teaching RT in an engineering department poses a major challenge. The technical literature on the subject, as well as the two books available up to 1974 [2, 3] are written for an audience of mathematicians and mathematical physicists, and are therefore largely unsuitable for direct classroom use. Some moderately sophisticated mathematical concepts are indeed essential to an understanding of the subject, but certainly much less than presupposed for the reader of the specialized literature. Furthermore, one needs to put into sharp relief the relevance of the subject to the engineering analysis of concrete problems, as well as the physical counterpart of what may at first sight appear unnecessary mathematical wizardry. In view of these difficulties, a set of classroom notes was prepared for the course at Delaware, three fourths of which (covering sections A-C of Table I) have now been published as a short book, "*An Introduction to Non-linear Continuum Thermodynamics*" [4].

RT is a wide and diversified field, so that teaching it implies deciding which grounds to cover, and even more crucially where to start. Every axiomatic science must start **somewhere**, and a few primitive undefined concepts are required, whose only specifications are the requirements laid down in the fundamental axioms. In RT, an

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**The philosophy of the course is non-traditional in three aspects . . . a thermodynamic theory of irreversible phenomena with no Onsager-type restriction to linearity is considered; a field theory of thermo is required; finally emphasis is placed on the role of constitutive assumptions in a thermo theory.**

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abstract mathematical structure may be developed, based on such primitive concepts as state and process [5, 6], and entropy is then obtained as a derived concept (see also Day [3]). One may also start from the notion of entropy, regarded directly as a primitive concept, as has been done in this course. This allows one to proceed much more quickly to results of direct engineering interest, though this choice invariably causes some

concern among professional scientists, who are not willing to accept entropy, particularly under non-equilibrium conditions, as a primitive undefined concept.

Indeed, among professional scientists an "acceptable" primitive concept is a physical quantity of which one is entitled to speak to colleagues

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**The most common reaction of the students after the course was to ask why they hadn't been taught thermo that way the first time they were exposed to the subject—apparently the most difficult part of the learning process was the unlearning of previously acquired biases.**

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without being asked to define it; or perhaps one which can be introduced in a paper without worrying that a referee may confute its meaningfulness in that context. Entropy of a system outside of equilibrium certainly does not meet these qualifications.

It turns out that in classroom use primitive concepts are, or are not accepted by students independently of their meeting these qualifications, and in spite of a long training aimed at avoiding their asking embarrassing questions, students are still open-minded enough to be about as likely to ask what a force is outside of equilibrium as they are to ask the same question about entropy—and the second question is not any more embarrassing than the first one. Indeed, at the end of the seventeenth century most scientists would have nothing to do with forces outside of equilibrium, and Newton felt the need to write: "*In Mathesi investigandae sunt virium quantitates et rationes illae, quae ex conditionibus quibuscumque positis consequentur; deinde ubi in physicam descenditur, conferendae sunt hae rationes cum phaenomenis ut innotescat quaenam virium conditiones singulis corporum attractivorum generibus competant. Et tum demum de virium speciebus, causis et rationibus physicis tutius disputare licebit*" [7]. Newton's statement, with "entropy" substituted for "force," could well be used today as a valid argument in favour of a theory of irreversibility which uses entropy as a primitive concept.

Comparison with the mechanical example of the concept of force is not the only illuminating

one; within the same body of thermodynamics the case of energy is an equally strong one. Energy is invariably presented as a primitive concept, the only specification for it being the requirements laid down in the first law; entropy and the second law are the exact counterpart. And indeed some rudimentary example of the validity of the second law is much easier to discuss and much more intuitive than any example of validity of the first law.

Furthermore, students may accept with some reservations the notion of entropy as a primitive concept, but they'll still allow the teacher to go on, and after a couple of classes they'll realize that scores of ideas which had been floating on shaky grounds in their previous thermodynamic training are now deduced with simple but rigorous logic from one unequivocal mathematical statement of the second law; they'll appreciate that by being asked to accept entropy as a primitive concept they are now offered **definitions** of reversibility, irreversibility, dissipation, and so on. They'll find out one can discuss mathematically and precisely mixtures and their properties without ever having to postulate the existence of semipermeable membranes; and what is invariably the stumbling block of any discussion about modern continuum thermodynamics among professional scientists is passed over smoothly and painlessly in the classroom. Indeed, the most common reaction of the students after the course in 1973 was to ask why they hadn't been taught thermodynamics in that way the first time they were exposed to the subject—apparently, the most difficult part of the learning process was the unlearning of previously acquired biases. (In fact, some satisfactory results have been obtained at the University of Naples, where some of the methodology of RT has been introduced in the teaching of thermodynamics at the undergraduate level.)

#### SCOPE OF THE COURSE

**T**HE CONTENTS OF the course, summarized in Table I, are illustrated in some detail in the following.

In Section A, 3 hours are dedicated to the introduction of tensors as linear transformations of Euclidean vector space into itself, and to the basic algorithm of space and time differentiation of vectors and tensors. Although the classroom notes and reference [4] include the algorithm for

**components** of vectors and tensors, this is really not required in the balance of the course and was not discussed in the classroom. The remaining two hours were dedicated to a few basic concepts of functional analysis, including topology of function spaces and Fréchet differentiation of functionals.

Section B was dedicated to traditional continuum thermodynamics, following the methodology of RT. Thus two results are obtained: the actual learning of classical thermomechanical theories of ideal fluids, viscous fluids and elastic solids, and the appreciation of the logical rigor, simplicity and mathematical compactness with which RT can yield the classical results. In particular, in section B1 the second law is written in the simple form requiring the rate of heat supply divided by temperature not to exceed the rate of increase of entropy; the classical elementary results of the thermodynamics of ideal fluids are then obtained as a direct consequence of the assumption that the state is identified by the instantaneous values of density and temperature. In section B2, the second law is written in the form of Clausius-Duhem's inequality, and shown to imply such classical results as the maximum possible efficiency of a heat pump without ever introducing a Carnot cycle. The general method

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**The traditional areas of transport phenomena and process dynamics; the new trends in molecular engineering, rheology and biochemical engineering may be compacted into some unifying central viewpoint: modern non-equilibrium thermo is a likely candidate for such a role.**

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of obtaining consequences of Clausius-Duhem's inequality in continuum thermomechanics constitutes the balance of Section B2. Throughout Section B, the only concrete examples of irreversibility which arise are heat transfer and viscous dissipation.

Section C is dedicated to the thermomechanics of polymers. In section C1, the method of RT is applied to the analysis of materials with memory, so that irreversibility of relaxation phenomena is discussed in general terms; Section C2 applies the results obtained to the specific case of polymeric materials. Heat transfer, flow and relaxa-

tion in polymers are discussed. The first three sections exhaust the contents of the textbook [4].

Section D covers the mathematical formalism of the methodology of RT as applied to both reacting and non-reacting mixtures. Since the aim is only to derive the classical equilibrium theory, diffusion is not discussed. In section D1, the general theory of internal state variables (such as the degree of conversion of a reaction and the degree of splitting into phases of mixtures) and their change in time, of affinity, and of both strong and weak equilibrium states is discussed; the irreversible nature of chemical reactions is put into sharp relief. In section D2, the axiomatic structure of classical chemistry is introduced. This allows to deduce rigorously the theory of physical and chemical equilibria, which are then discussed in detail in section E.

#### **FUTURE EVOLUTION**

**T**HE COURSE DESCRIBED above has been given both in 1973 and 1974, and taken by almost all the graduate students of the department during their first semester of work. In the Fall semester of 1974, a seminar was also held, meeting once a week, on the teaching of thermodynamics at both the graduate and undergraduate level. The following future evolution of graduate level teaching of Thermodynamics has been planned.

The students will be offered two graduate courses; the first one, to be taken in their first year of work, will be a more traditional course than the one described above, while a course in modern continuum thermodynamics will be offered to second-year graduate students starting in the Fall semester of 1976. With the background of a more traditional course, the material in sections D2 and E could well be left out from the second year course, and the 12 hours so recovered could be used for covering one or more of the following subjects:

- **Thermodynamics of diffusion.** This would complete the landscape of the theory of irreversibility of the four basic classes of phenomena of interest to chemical engineers, namely momentum, heat and mass transfer and chemical kinetics.
- **Thermodynamics and stability.** This would fit in very well with some of the strong research interests of the Department, namely stability of non-equilibrium states (flow patterns, chemical

kinetics) and control theory. The connection between process dynamics, stability theory and thermodynamics has been the subject of some very interesting research [8, 9].

• **Relationship between continuum thermodynamics and statistical thermodynamics.** Although RT is strictly a phenomenological continuum theory, it is by no means at odds with statistical thermodynamics; the aim of the latter is to obtain a priori predictions on the constitutive properties of specific materials, while one of the main aims of the former is to obtain general restrictions on the allowable forms of the constitutive equations imposed by the second law. Particularly in the case of polymeric materials, the two approaches may be complementary, as shown by some recent research [10]. Also, the structural modeling of materials may put some of the basic axioms of RT in a correct physical perspective: witness the case of material objectivity, which has been shown to be valid only if Coriolis forces on structural elements can be neglected [11, 12].

It is perhaps interesting, before concluding, to examine the role of thermodynamics teaching in ChE in a historical perspective. ChE has undergone, at twenty years intervals, two major reorganizations of its patterns of thought, research and teaching. In the late 1930's, ChE evolved from the early stage where the emphasis was on Industrial Chemistry of Processes, to the stage where Unit Operations were seen as the core. In the late 1950's, the new change was the switch from Unit Operations to Transport phenomena. Both changes, when looked upon from a distance in time, have the same character: unification of a variety of parallel elements which had grown too large for detailed analysis (the chemical processes up to 1930, the unit operations up to 1950) into a more compact form which allows the traditional material to be seen from some central viewpoint.

A somewhat similar evolution may be in the making, and the late 1970's appear as just about the right time. The traditional areas of transport phenomena and process dynamics; the new trends in molecular engineering, in rheology and in biochemical engineering may be compacted into some unifying central viewpoint; and modern non-equilibrium thermodynamics is a likely candidate for such a role. The trend is already showing up

concretely in the area of transport phenomena: two recent books on the subject [13, 14] dedicate a substantially larger fraction of their contents than traditional to the role of thermodynamics in the theory of transport phenomena.

The course given at Delaware in 1973 and 1974 is a first effort in this direction; inclusion of sections F, G and H would extend the area of thermodynamic influence to the whole of transport phenomena, to process dynamics, molecular engineering and rheology, with only biochemical engineering left out. Of course, this would still be only an initial effort, which should and could extend to the methodology of teaching and thinking at the undergraduate level. Equally of course, the traditional areas of physical and chemical equilibria, energy balances and ideal fluids should not be excluded from thermodynamics, but neither should they be regarded as exhausting the subject. □

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## HETEROGENEOUS CATALYSIS

W. N. DELGASS

Purdue University

West Lafayette, Indiana 47907

AS THE BACKBONE of the chemical and petroleum industries and a key to the solution of current problems concerning energy and the environment, heterogeneous catalysis is firmly rooted in the domain of chemical engineering. The intersection of chemistry, physics, and engineering in catalysis provides a broad spectrum of intriguing fundamental and practical questions. The breadth and complexity of the subject, however, require a balance of survey versus depth in presentation of material in a one semester graduate course. The choice of organization and specific topics must be geared to the make-up of the class as well as to the prejudices of the instructor.

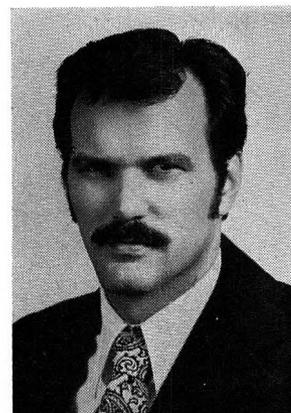
At Purdue a class of 25 students in this course may include chemists (~15%), chemical and non-chemical engineers bound for the Ph.D.,

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**Heavy reliance on original papers slows the pace but helps achieve one of the course goals—familiarity with the literature and the ability to read it critically.**

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Master's and, in a few cases, B.S. degree. This diverse class background and the desire to make the course available at the graduate level without prerequisites necessitate inclusion of a review of chemical kinetics. The prejudice of the instructor has dictated organization of the course primarily in terms of theoretical concepts. No text with the orientation and emphasis outlined in Table 1 is available, but J. M. Thomas and W. J. Thomas, *Introduction to the Principles of Heterogeneous Catalysis*, Academic Press, New York (1967), supplemented by Alfred Clark's



W. N. Delgass received his B.S. degree in Chemical Engineering from the University of Michigan and M.S. and Ph.D. degrees from Stanford University. He joined the Yale faculty as an Assistant Professor of Engineering and Applied Science in 1969 after a post-doctoral year at the University of California, Berkeley. In 1974 he became an Associate Professor of Chemical Engineering at Purdue University. His principal research interests are heterogeneous catalysis, surface chemistry, Mossbauer and x-ray photoelectron spectroscopy.

book *The Theory of Adsorption and Catalysis*, Academic Press, New York (1970), or J. J. Thompson and G. Webb, *Heterogeneous Catalysis*, John Wiley and Sons, Inc., New York (1968), represents a reasonable compromise. Additional sources of material and some key papers read by the students and discussed in class are also included in Table 1. Heavy reliance on original papers slows the pace but helps to achieve one of the course goals: familiarity with the literature and ability to read it critically.

### PROVIDING ORIENTATION

DETAILS OF THE COURSE material are best discussed with reference to Table 1, which also indicates the approximate class time spent on each area. Section I was an experiment last year to provide orientation to the field and motivation for the array of topics that follows. Sinfelt's elegant investigation of ethane hydrogenolysis over supported metals proved to be a good vehicle for this purpose, in spite of difficulties the students had initially in dealing with terms and concepts that were not fully developed until later in the course.

Sections II, III and IV of the course outline represent a view of catalysis from the gas side of the gas-solid interface and also include details of physical characterization of catalysts. The emphasis in Sections III and IV is on establishing criteria for the validity and chemical significance of kinetic parameters. Simple expectations such as the exothermicity of adsorption or a rate of adsorption not exceeding the collision rate with the surface, for example, can help prevent a computer's propagating physical or chemical nonsense from a mathematical fit of kinetic data. Working knowledge in this area is stressed through homework problems and student reviews of recent papers presenting kinetic analyses. A more complete review of kinetics and quantitative discussion of design and heat, mass and momentum transfer in chemical reactors is the province of "Chemical Reactor Design," which, along with courses in thermodynamics, transport, and mathematics, makes up the graduate core curriculum in chemical engineering at Purdue.

Sections V and VI present a view of catalysis from the solid side of the gas-solid interface. These sections contain much new subject matter and are the most difficult for many students. The material is presented to help students establish a basis for the understanding and construction of chemical models for catalyst behavior and to provide them with criteria for comparing different catalysts. Unique explanations of the catalytic action are difficult to achieve, but concepts such as ensemble, or surface geometry, effects on catalytic selectivity and modification of the electronic properties of metal surfaces by alkali adsorption or semiconductor surfaces by contact with metals, for example, can contribute to progress in the field. Section VII reinforces some of these concepts, introduces others, and also provides discussion of industrial applications of catalysis. Many students choose deeper study of industrial reactions for their term papers.

## EXPERIMENTAL TECHNIQUES

**A**N APPARENT OMISSION in the outline is a general section on experimental techniques. This area is covered in literature readings, a tour of the extensive catalysis research facilities in the School of Chemical Engineering, the term paper option, and a requirement that teams of two students prepare for distribution to the class a one page summary of a particular technique.

The summary includes the underlying principles, experimental requirements, information available, catalytic applications, and a few directive references. Though after several revisions a notebook of these descriptions of experimental techniques will become quite useful, future versions of the course will provide more direct discussion of this area through further integration of sections V, VI and VII. □

TABLE 1  
Course Outline

- I) OVERVIEW (4 Lectures)—Discussion of "Catalytic Hydrogenolysis over Supported Metals," J. H. Sinfelt, *Catal. Rev.*, 3; 175 (1969)  
*Emphasis:* The nature of catalysts and catalysis research.
- A) Relation of Hydrogenolysis to Petroleum Processing—Catalyst Selectivity
  - B) Nature of Catalysts
    - 1) Support
    - 2) Metal Dispersion and its Measurement
    - 3) Methods of Preparation
  - C) Kinetic Analysis
  - D) Comparison of Group VIII Metals
    - 1) Activity Pattern
    - 2) Correlation of Activity with Electronic Properties
    - 3) Crystallite Size Effects
    - 4) Support Effects
    - 5) Ru/Cu Bimetallic Clusters (J. H. Sinfelt, *J. Catal.*, 29, 308 (1973))
- II) CHEMICAL KINETICS (8 Lectures)—(M. Boudart, *Kinetics of Chemical Processes*, Prentice Hall, 1968)  
*Emphasis:* The relation between sequences of elementary steps and the rate expression, recognition of valid kinetic parameters.
- A) Derivation of Rate Equations from Sequences of Elementary Steps
    - 1) Langmuir Adsorption
    - 2) Steady State Approximation
    - 3) Rate Determining Step Approximation
  - B) Rate Constants for Elementary Steps—Orders of Magnitude
    - 1) Transition State Theory
    - 2) Collision Theory
    - 3) Further Evaluation of Rate Parameters, (M. Boudart, D. E. Mears, and M. A. Vannice, *Ind. Chim. Belge.*, Special Issue 36, Part I, 281 (1967), and M. Boudart, *AIChE Journal*, 18, 465 (1972))
  - C) Correlation and Estimation of Kinetic Parameters
    - 1) Polanyi Relation
    - 2) Van Tiggelen Formula
    - 3) Principle of Sabatier
    - 4) Compensation Effect
  - D) Non-Uniform Surfaces
    - 1) Freundlich and Temkin Isotherms
    - 2) 2 Step Reactions

Experimental techniques are covered by requiring teams of two students to prepare for distribution to the class a one page summary of a popular technique . . . including the underlying principles, experimental requirements, information available, catalytic applications and a few directive references.

### III) SURFACE AREA AND PORE STRUCTURE

(3 Lectures)

- A) Selective Chemisorption
- B) BET Theory—Approximations, Results and Applications
- C) Pore Size Distribution
  - 1) Kelvin Equation
  - 2) Hysteresis in BET Isotherm
  - 3) Mercury Porosimetry

### IV) HEAT AND MASS TRANSFER INFLUENCE ON KINETIC PARAMETERS (4 Lectures)

(C. N. Satterfield, *Mass Transfer in Heterogeneous Catalysis*, MIT Press, (1970))

*Emphasis*: Qualitative behavior, diagnostics to insure true kinetics.

- A) Bulk or Film Diffusion
- B) Pore Diffusion
  - 1) Macropore
  - 2) Micropore
- C) Heat and Mass Transfer Diagnostics (P. B. Weisz and J. S. Hicks, *Ch.E. Science*, 17, 265 (1962))
- D) Diffusion Influence on Selectivity
- E) Poisoning

### V) PROPERTIES OF SOLIDS (7 Lectures)

*Emphasis*: Development of important parameters and differences between classes of solids.

- A) Crystal Structure
  - 1) Crystal Lattices
  - 2) Miller Indices
  - 3) Geometry of Surface Planes
- B) Electronic Structure
  - 1) Review of Atomic and Molecular Orbitals
  - 2) Band Structure
    - a) Metals
    - b) Semiconductors—Intrinsic/Extrinsic
    - c) Insulators
    - d) Temperature Dependence of Conductivity
  - 3) Image Potential
  - 4) Work Function—Changes on Adsorption
  - 5) Collective vs. Localized Electron Picture

### VI) THEORETICAL CONCEPTS IN ADSORPTION AND CATALYSIS (8 Lectures)

*Emphasis*: Examination of the degree to which simple theoretical approaches can describe catalytic phenomena.

- A) Metals
  - 1) Ionic Model for Adsorption
  - 2) Localized Covalent Model for Adsorption
  - 3) Summary of Current Theoretical Approaches to Metal-Adsorbate Bonding
  - 4) Ensemble vs. Ligand Effects (Y. Soma-Noto and W.M.H. Sachtler, *J. Catal.*, 32, 315 (1974))

- a) CO Adsorption—Bridged and Linear
- b) Alloy Surfaces
- c) Infrared Spectroscopy

### B) Non-Metals

- 1) Boundary Layer Theory of Adsorption on Semiconductors
  - a) Depletive/Cumulative
  - b) N<sub>2</sub>O Decomposition
- 2) Catalyst/Support Electronic Interaction
  - a) Metals on Semiconductors
  - b) Semiconductors on Metals
- 3) Thermochemical Approach—CO Oxidation Over NiO
  - a) Carbonate Intermediate
  - b) <sup>18</sup>O Isotope Tracer
- 4) Ligand Field Approach

### VII) CATALYTIC REACTIONS AND CATALYTIC CHEMISTRY (11 Lectures)

#### A) Oxidation

- 1) Summary of Industrial Processes and Catalysts
- 2) Ethylene to Ethylene Oxide
  - a) Unique Selectivity of Ag
  - b) O<sub>2</sub><sup>-</sup> Intermediate (P. A. Kilty, N. C. Rol-and W.M.H. Sachtler, in *Catalysis*, Vol. 2, J. W. Hightower ed., North Holland (1972) p. 929)
  - c) Radiation Induced Selectivity Change (J. J. Carberry, G. C. Kuczynski, and E. Martinez, *J. Catal.*, 26, 247 (1972))
    - i) Importance of Surface Ca Impurity
    - ii) X-ray Photoelectron Spectroscopy

#### B) Hydrogenation (R. J. Kokes, in *Catalysis*, Vol. 1, J. W. Hightower ed., North Holland (1972), p. A-1)

- 1) Comparison of Metals and Metal Oxides
- 2) Propylene on ZnO—Details of Catalytic Chemistry

#### C) Cracking

- 1) Summary of Industrial Processes
- 2) Carbonium Ion Reactions
- 3) Brönsted and Lewis Acid Sites on Silica/Alumina and Zeolites

#### D) Reforming

- 1) Dual Functional Catalysts
- 2) Dehydrocyclization on Clean Surfaces (G. A. Somorjai, *Catal. Rev.*, 7, 87 (1972))—Relation between Clean Surface Research and Catalysis

#### E) NO Reduction

- 1) Summary of Auto Exhaust Problems
- 2) Molecular Orbital Symmetry Rules—2NO ⇌ N<sub>2</sub> + O<sub>2</sub> as a Symmetry Forbidden Reaction

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# DYNAMICAL SYSTEMS AND MULTIVARIABLE CONTROL- An Operations Research Approach To Automatic Control Education

W. A. GRUVER

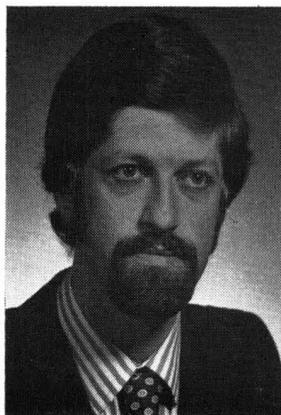
*North Carolina State University  
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AT MOST UNIVERSITIES in the United States, graduate education in automatic control is the responsibility of each of the traditional engineering departments—chemical, electrical and mechanical. This situation is partly a result of the rapid growth of control during the past 30 years, which has emphasized limited areas of application and, thereby, created groupings such as process control, servo control and flight control. In spite of these groupings, there has been considerable emphasis at the graduate level on mathematical aspects of automatic control and less emphasis on practical questions of system modeling and control implementation.<sup>1, 2</sup> This emphasis has led to the distinction “classical” or “modern” control which, in turn, has magnified the gap between theory and practice. It is generally recognized that sole emphasis on mathematics does not necessarily provide the best preparation for a career in automatic control. In addition to an appreciation of mathematical abstraction, a broadness of perspective toward system design is needed in order to solve the emerging problems of our society. According to the late L. Hyldgaard-Jensen:

“Engineering education of the future should realize that our industrial systems are becoming so large and so complex that knowledge of the parts taken separately is not sufficient. On the contrary we can expect that, often, the interconnections and interactions between the system elements will be more important than the separate elements themselves . . . Therefore the teaching of design in automatic control will exhibit an increasing emphasis upon new, explicit, and highly organized

techniques for dealing with system structures. The shift in viewpoint from analysis of systems to design of systems and the formal emphasis upon the process of interconnecting elements into total systems will bring about a new tendency in automatic control education.”<sup>3</sup>

At North Carolina State University (NCSU), a broad outlook toward Systems and Control is encouraged by its centralization within Operations Research (OR). Although the association of automatic control and operations research is not new,<sup>4</sup> the unique feature at NCSU is that OR is a graduate program of multidisciplinary nature, supported by faculty from most branches of



William A. Gruver is a graduate of the University of Pennsylvania (PhD, 1970) and Imperial College, London (DIC, 1965). Before joining the faculty at North Carolina State University in 1974, he worked as an optimization specialist for the German Space Agency and has taught electrical engineering at the University of Pennsylvania and the U.S. Naval Academy. In 1973 he was recipient of a Humboldt Senior Scientist Award at the Technical University Darmstadt. At NCSU, Dr. Gruver is active in developing an interdisciplinary program in the systems optimization and control area, and the use of laboratories in automatic control education. His research centers on the computational and algorithmic aspects of mathematical programming and optimal control.

engineering and the physical sciences. Study in OR can be undertaken in one or more of the following areas: mathematical optimization, stochastic systems, econometrics, information and computer sciences, and dynamical systems and automatic control. Students in OR usually have degrees in engineering, mathematics, statistics or computer science.

The main characteristic of Operations Research during its brief history is that it is interdisciplinary. That is, it draws on mathematics, economics, physics and engineering and distills from among these disciplines, techniques which apply to the system under study with the objective of gaining understanding of the system so that it may be controlled and harnessed for man's needs. The natural means for broadening the scope of automatic control education at NCSU, therefore, has been to associate it with the Operations Research Program. An important benefit of this association is the rich heritage of OR with mathematical programming and numerical optimization techniques which interfaces directly with the theory and computational methods of optimal control.

**D**YNAMICAL SYSTEMS and Multivariable Control is a one semester, first year graduate level course in the Systems and Control option of the Operations Research Program. Prerequisites are a knowledge of differential equations and linear algebra as usually contained in an undergraduate engineering curriculum. A rudimentary knowledge of the Fortran language and card preparation is also required. The customary prerequisite of an undergraduate course in single-loop feedback systems and frequency response methods is intentionally omitted in order that the course can be taken by non-engineers. Most students with a major in OR also have backgrounds which include advanced calculus and probability theory.

This course is intended to (1) provide an introduction to analytical modeling, control and optimization of dynamical systems, (2) create an awareness of the wide range of application of Systems and Control and (3) provide experience in computer-aided analysis and design. Both state space and transfer function descriptions are developed early in the course so that the student is not led to regard either approach as "classical" or "modern." Emphasis is placed on linear, stationary models with parallel development of continuous-time and discrete time

representations. Topics include state variables, transforms, flow graphs, canonical forms, system response, stability, controllability and observability, modal control, non-interacting control and fundamental concepts of optimal control and estimation. Multidisciplinary applications are

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**The emphasis on the mathematical aspects of automatic control has magnified the gap between theory and practice. It does not necessarily provide the best preparation for a career in automatic control.**

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chosen from biological, chemical, electrical, mechanical and socio-economic systems.

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

<b>System Representation—</b>	State variables, state equations, transfer functions, Laplace and z-transforms, canonical forms and transformations of linear systems.
<b>System Response—</b>	Vector differential equations, transition matrix, eigenvector analysis, controllability and observability, phase plane, system simulation.
<b>System Stability—</b>	Equilibrium points and stability concepts, Direct Method of Lyapunov, construction of Lyapunov functions, Routh-Hurwitz criteria, root locus.
<b>Multivariable Control Systems—</b>	State space formulation, matrix transfer functions, decoupling and non-interacting control, feedforward and modal control, observers.
<b>Linear Stochastic Systems—</b>	Statistical concepts in time and frequency domains, Gauss-Markov random processes, mean square estimation and optimal filtering.
<b>Optimal Control Systems—</b>	Maximum Principle, Dynamic Programming, linear systems subject to quadratic criteria, combined optimal control and estimation.

#### **INTERDISCIPLINARY SPIRIT**

**T**HERE ARE PRESENTLY several excellent textbooks that combine the state variable

**Although the association of automatic control and operations research is not new, the unique feature at NCSU is that OR is a graduate program of multidisciplinary nature, supported by faculty from most branches of engineering and the physical sciences.**

and transfer function approaches at an introductory level. Most of these books, however, emphasize applications from electrical engineering. In keeping with the interdisciplinary spirit of this course, the textbook by Takahashi, Rabins and Auslander<sup>5</sup> provides an effective treatment of the material while keeping a good balance between mathematical abstraction and physical reality. The first half of the course includes use of a computer program for obtaining time response, system reduction to canonical form, system sensitivity by root locus, etc. This program is an expanded version of a package for the analysis and design of linear state variable feedback systems. The user's manual is reasonably complete and gives sample problems for testing the routines.<sup>6, 7</sup>

The second part of the course is concerned with use of the system theoretical concepts studied previously and is intended to serve as an introduction to topics which may be studied in more advanced courses or independent study basis. The topic of multivariable control treats both state variable and transfer function approaches, although advanced frequency response techniques such as the inverse Nyquist array method have not been included due to lack of time and need for additional preparation in complex variable theory.

The topics of stochastic and optimal systems survey, in the remaining time, certain fundamental concepts of these areas and present some current applications which have included power, ecological and transportation systems. Several class sessions and homework exercises are also devoted to the use of a computer program, the Variable Dimension Automatic Synthesis Program (VASP), for implementing some of the optimal estimation and control algorithms.<sup>8</sup> Experience gained from working with these computer-aided design programs has been a valuable means of integrating theoretical concepts with physical reality, particularly when a student is forced to discover why his program bombed!

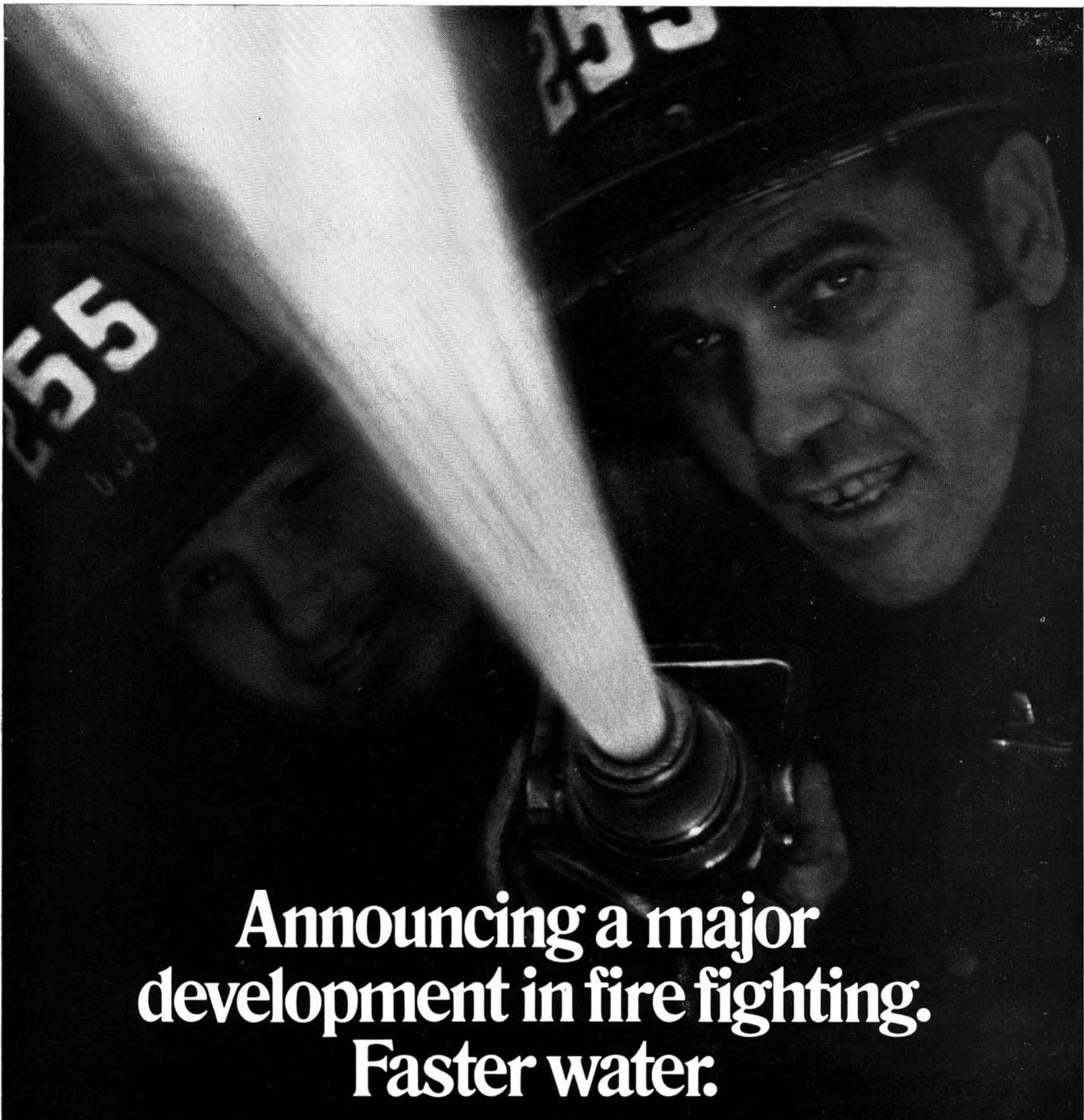
The class meets three hours per week for 16 weeks. About 6 weeks are devoted to system representation, response and stability. The remaining time is divided equally among the topics of multivariable control, stochastic systems and optimal control. A graduate student teaching assistant is responsible for setting up the computer exercises and serves as programming consultant.

The brief exposure to system optimization is intended to interface with related OR courses which included linear and nonlinear programming, dynamic programming, optimization of engineering processes, variational methods in optimization techniques, vector space methods in system optimization, and computational algorithms of mathematical programming and optimal control. Cognate courses such as process dynamics, economic decision theory, biomathematics and statistical communication theory provide depth in more specialized topics.

Centralization of this course within the Operations Research Program avoids the usual groupings such as process control, servo control or flight control and, thereby, encourages a broad outlook toward applications in the Systems and Control area. An important benefit of this association is the rich heritage of OR with mathematical programming and numerical optimization techniques which interfaces directly with the theory and computational methods of optimal control. □

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## DIGITAL COMPUTATIONS FOR CHEMICAL ENGINEERS

Y. A. LIU  
Auburn University  
Auburn, Alabama 36830

A NEW GRADUATE COURSE on "*Digital Computations for Chemical Engineers*" has been developed recently by the author at Auburn University. The major objective of the course is to introduce to the student the theory and application of the polynomial (or functional) and finite difference approximations in the solution of mathematical models in ChE. Brief discussions on the use of these approximation techniques in the analysis of experimental data are also included.

The contents of the course are distributed into three broad topics: I. Introduction to polynomial approximation and finite difference, II. Numerical solution of ordinary differential equations (ODE), and III. Numerical solution of partial differential equations (PDE). The progression of the course follows the sequence given in Table I, which lists the breakdown of the course in parts and chapters. The course is divided into two three-credit-hour quarter-courses. The first three-fifths of the topics is covered in ChE 600, "ChE Analysis," and the remainder in ChE 650, "Special Topics in ChE." As Seen in Table I, the course puts less emphasis on the computational solution of system of linear and nonlinear algebraic equations as well as the boundary value problems in ODE. These topics are discussed only briefly within Topics II and III, and are covered in more depth in courses on computer aided process design and optimal control of process systems. Although a number of the recent textual references are given in Table II, a single textbook which is suitable for the course does not exist. Consequently, lecture notes have to be prepared for the course. However, note-taking during the lectures is eliminated through the use of detailed handouts on most of the lecture material.

Referring to Tables I and II, a few remarks on the course contents and the source of the course material are as follows. Topic I contains a concise introduction of polynomial approximation and finite difference, with special emphasis on their applications to the computational analysis of experimental data. The problem of finding a polynomial of a specified degree to approximate a known function given either in an analytical form or as sets of discrete data is considered. The important questions related to this problem are discussed from the approximation theory<sup>1</sup> using finite difference table and associated linear symbolic operators.<sup>2</sup> The actual lectures follow much of the standard material on polynomial approximation and finite difference from reference texts 2, 5, 6, 10, and 12 in Table II. The reported

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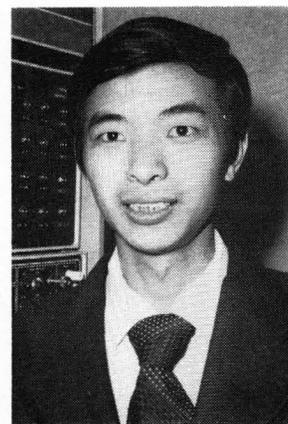
**The major objective of the course is to introduce to the student the theory and application of the polynomial (or functional) and finite difference approximations in the solution of mathematical models in chemical engineering.**

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results on the development and implementation of computational algorithms on the topic subject from such periodicals as *Communications of the Association for Computing Machine (CACM)* and *Numerische Mathematik* are discussed. An index by subject on these algorithms published in 1960-1970 is conveniently available in the reference text 4 in Table II. Weekly homework problems on applying the lecture material to such problems as the interpolation of discrete data of vapor pressure versus temperature, the differential and integral methods of kinetic analysis from experimental data are given. A special problem on the practical application of spline approximation to the analysis of thermodynamic data<sup>3, 4</sup> is also assigned.

**TABLE I.**  
**A TOPICAL OUTLINE OF THE COURSE**

- I. INTRODUCTION TO POLYNOMIAL APPROXIMATION AND FINITE DIFFERENCE:**
- (1) Topics—polynomial approximation, finite difference, interpolation and extrapolation, numerical differentiation and integration, orthogonal polynomials and quadrature formulas.
- (2) Selected Application—analysis of thermodynamic data by the spline approximation technique.
- II. NUMERICAL SOLUTION OF ORDINARY DIFFERENTIAL EQUATIONS (ODE):**
- (1) Topics—fundamental concepts, Runge-Kutta and allied single-step formulas, predictor-corrector methods, stability of multistep and Runge-Kutta methods, stiff differential equations.
- (2) Selected Application—digital parameter estimation of complex chemical reaction systems.
- III. NUMERICAL SOLUTION OF PARTIAL DIFFERENTIAL EQUATIONS (PDE):**
- Chapter III-1. Fundamental Concepts**  
Fundamental notations, first and second order PDE, system of first order PDE, initial and boundary conditions, finite difference approximation, functional approximation, further mathematical background, questions raised.
- Chapter III-2. Methods of Lines (MOL) and Method of Characteristics (MOC)**  
Introduction, basic concepts in the MOL, inverse methods, consistency, convergence and stability, MOL for parabolic, hyperbolic and elliptic PDE, method of characteristics, other extensions.
- Chapter III-3. Finite Difference Solution of Parabolic Equations**  
Introduction, model parabolic PDE, explicit and implicit finite difference approximations, consistency and convergence, heuristic, Von Neumann and matrix stability concepts, some extensions, solution of finite difference approximations, composite solutions-global extrapolation and local combinations, explicit and implicit methods for two- and three-dimensional problems—alternating direction, local one dimension, fractional splitting and hopscotch methods, other extensions.
- Chapter III-4. Finite Difference Solution of Hyperbolic Equations**  
Introduction, model hyperbolic PDE, first order hyperbolic PDE, first order vector and vector conservative hyperbolic PDE, two- and three-dimensional hyperbolic PDE, second order model hyperbolic PDE, other extensions.
- Chapter III-5. Finite Difference Solution of Elliptic Equations**  
Introduction, model elliptic PDE, finite difference approximations of two- and three-space dimensional problems, solution of finite difference approximations—direct methods, iterative methods,



Y. A. Liu did his undergraduate work at National Taiwan University, graduate study at Tufts University and obtained his Ph.D. from Princeton University in 1974 under Professor Leon Lapidus. He has been an assistant professor of the Department of Chemical Engineering at Auburn University since 1974. He is currently working on research projects in the areas of applied numerical methods, process modeling, simulation and optimization, systems theory and process control, process design and synthesis, applied chemical kinetics, statistical theory of particulate processes, coal liquefaction and solid-liquid separation.

- sparse matrix techniques, composite solutions and other methods, conversion of elliptic to hyperbolic or parabolic equation, other extensions.
- Chapter III-6. Variational, Least-Square and Moment Methods**  
Introduction, variational principles, Rayleigh-Ritz method and extensions, variational solution of parabolic, hyperbolic and elliptic PDE, dynamic programming and invariant imbedding approach, least-square and moment methods, comparison with other methods, further extensions.
- Chapter III-7. Galerkin Methods**  
Introduction, general features of Galerkin methods, solution of parabolic PDE-continuous-time Galerkin, Crank-Nicholson Galerkin, hopscotch-Galerkin, local one dimensional Galerkin methods, solution of hyperbolic and elliptic PDE, comparison with other methods, further extensions.
- Chapter III-8. Collocation Methods**  
Introduction, collocation points and approximating polynomials, the line collocation, orthogonal collocation and finite element collocation methods, solution of parabolic, hyperbolic and elliptic PDEs, comparison with other methods, further extensions.
- Chapter III-9. Finite Element Methods**  
Introduction, variational finite element methods, weighted-residual finite element method, element types and basis functions, the time dimension, finite element matrix structure and storage schemes, solution of linear equations in finite element analysis, solution of parabolic PDE-finite element heat and mass transfer analysis,

solution of hyperbolic PDE, solution of elliptic PDE-finite element method and fluid flow problems, comparison with other methods, further extensions.

Chapter III-10. Practical Considerations in Polynomial (Functional) Approximation Methods

Introduction, continuous and discrete methods of weighted residuals, the selection of weighting functions, the selection of approximating functions, the problem specific polynomial approach, further extensions.

Chapter III-11. Selected Applications

Introduction, solution of Navier-Stokes equations, solution of problems of adsorption, chromatography and ion exchange columns, solution of oil and gas reservoir problem, solution of phase change and related moving boundary problems, solution of water resources problems, solution of population balance equations, solution of catalytic fixed bed reactor problem.

## ORDINARY DIFFERENTIAL EQUATIONS

**I**N TOPIC II, the fundamental concepts and definitions in numerical solution of ODE are introduced. The practical considerations in numerically solving ODE such as stability, accuracy and computational efficiency are also considered. Here, the important material from three recent books 4, 7, and 8 in Table II is briefly discussed, and supplemented with the excellent monograph on stiff ODE edited by Willoughby (see Table II). The specific lectures begin with some basic techniques for deriving integration formulae for ODE and related terminologies. The Taylor series expansion is used first to derive the simplest Euler's formula and the concept of truncation error. The forward and backward Taylor series expansions are then combined to derive the midpoint rule. These two integration formulae provide the typical examples for defining the explicit as well as the single-step and multi-step methods. Next, both the Euler's formula and midpoint rule are derived by using numerical differentiation and/or integration formulae. The integration of the ODE by the trapezoidal rule gives the modified Euler's formula, which serves as an example for introducing the implicit method. The combined use of the Euler formula, the original ODE and the modified Euler's formula suggests the family of predictor-evaluation-corrector-evaluation (PECE) methods. A generalized, linear, multi-step differential-difference equation with constant coefficients is then defined to summarize the preceding discussions concisely and to encompass all previous integration formulae with-

in the same framework. The course is continued with the illustration of the concept of order by deriving, for example, the second-order Adams-Bashforth predictor equation from polynomial approximation. With these preliminaries in hand, the next step in the course is to introduce the generalized Adams-Bashforth formulae, the Adams-Moulton's forms and the Nystrom explicit forms, etc. The well-known Runge-Kutta processes are discussed in a vector-matrix form<sup>5</sup> and applied to many homework problems. At this time, a special topic on the parameter estimation in ODE from experimental data is given. A generalized nonlinear least-square, curve-fitting procedure<sup>6, 7</sup> is introduced and a problem of computerized kinetic analysis in the batch fermentation of penicillin is assigned to the students. The effectiveness and comparison of different methods in solving ODE are then presented.<sup>8, 9</sup> Topic II is concluded with lectures on the occurrence of stiff ODE in chemical engineering,<sup>10</sup> and several efficient integration packages for solving stiff ODE such as by Gear.<sup>11</sup> Finally, many interesting papers on stiff ODE from the reference text 15 in Table II are discussed.

## PARTIAL DIFFERENTIAL EQUATIONS

**A**LTHOUGH A CONSIDERABLE amount of the latest knowledge on the numerical solution of PDE by polynomial (or functional) approximation has been reviewed in reference texts 3, 13, and 17 in Table II, such texts on the numerical solution of PDE by finite difference as 1, 6, 9-11, 14-16 in Table II contain only that literature published before 1970. A suitable book covering the up-to-date information of both types of approximations does not exist. Thus, the lecture-notes for Topic III are mostly the original developments in the course. An outline in chapters and sections has been included in Table I. It should be mentioned that the developments of

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**The problem of finding a polynomial of a specified degree to approximate a known function given either in an analytical form or as sets of discrete data is considered . . . questions related to this problem are discussed from the approximation theory using finite difference table and associated linear symbolic operators.**

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these notes would not be possible without the encouragement, support and participation of Professor Leon Lapidus of Princeton University. The computer listing of the latest publications as well as the hundreds of reference reports and reprints on the numerical solution of PDE given by Professor John H. Giese of University of Delaware have been most helpful. In addition, a number of excellent literature reviews and the latest developments on the subjects on Topic III have been found in several recent doctoral dis-

sertations. For example, studies which are concerned with the method of line for PDE<sup>12</sup> (Chapter III-2), the composite numerical solution of PDE<sup>13</sup> (Chapter III-3 to III-5), finite element method for heat conduction analysis<sup>14</sup> and fluid flow problems<sup>15</sup> (Chapter III-9), collocation

**TABLE II.**  
**SOME TEXTUAL REFERENCES OF**  
**THE COURSE**

1. Ames, W. F., "Numerical Solution of Partial Differential Equation," Barnes & Nobles (1969).
2. Dahlquist, G., A. Bjorck, & N. Anderson, "Numerical Methods," Prentice-Hall (1974).
3. Finlayson, B. A., "The Method of Weighted Residuals and Variational Principles," Academic Press (1972).
4. Gear, C. W., "Numerical Initial Value Problems in Ordinary Differential Equations," Prentice-Hall (1971).
5. Issacson, I., & H. B. Keller, "Analysis of Numerical Methods," Wiley (1966).
6. Lapidus, L., "Digital Computations for Chemical Engineers," McGraw-Hill (1962).
7. Lambert, J. D., "Computational Methods in Ordinary Differential Equations," Wiley (1973).
8. Lapidus, L., & J. H. Seinfeld, "Numerical Solution of Ordinary Differential Equations," Academic Press (1971).
9. Mitchell, A. R., "Computational Methods in Partial Differential Equations," Wiley (1969).
10. Ralston, A., & H. S. Wilf, Editors, "Mathematical Methods for Digital Computers," Wiley, Vol. I (1960), and Vol. 2 (1967).
11. Richtmyer, R. D., & K. W. Morton, "Difference Methods for Initial Value Problems," 2nd Edition, Interscience (1967).
12. Rosenbrock, R. H., & C. Storey, "Computational Techniques for Chemical Engineers," Pergamon Press (1966).
13. Strang, G., & G. Fix, "An Analysis of the Finite Element Method," Prentice-Hall (1973).
14. Varga, R. S., "Matrix Iterative Analysis," Prentice-Hall (1962).
15. Willoughby, R. A., Editor, "Proceedings of International Symposium on Stiff Differential Systems," Wilbad, Germany, Plenum Press (1974).
16. Young, D. M., "Iterative Solution of Large Linear Systems," Academic Press (1972).
17. Zienkiewicz, O. Z., "The Finite Element Method in Engineering Science," 2nd Edition, McGraw-Hill (1967).

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**A generalized non-linear least square, curve-fitting procedure is introduced and a problem of computerized kinetic analysis in the batch fermentation of penicillin is assigned . . . the effectiveness and comparison of different methods in solving ODE are then presented.**

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method for the analysis of chromatographic system<sup>16</sup> (Chapter III-8) have been reported. While further discussions on the course contents and source material for Topic III are not possible within the limits of this article, a detailed write-up and specific subject references on the numerical solution of PDE can be obtained by writing to the author.

**WORK REQUIREMENTS**

**A** BRIEF REMARK about the course requirement may be of interest here. Homework problems are assigned to the class weekly. Each student is required to conduct an independent course project and to submit a term paper which includes: (a) a concise literature survey of the most important publications in the topic chosen, (b) a critical analysis of the computational techniques involved and a proper evaluation of the "state of the art," and (c) suggestions for further investigations as well as a preliminary analysis of the feasibility of the proposed research areas. Since no course examinations are given, this provides more opportunities for each student to pursue the specific subjects of interest. Typical subjects on the term projects chosen by the class during the last year include the method of characteristics, the method of lines, the analysis of chromatographic system, the collocation method, and the extrapolation technique for the solution of PDE and nonlinear algebraic equations. It is encouraging to mention that several of these projects conducted by the class in the course have led to some quite original research

(Continued on page 202.)

## INDUSTRIAL POLLUTION CONTROL

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**I**N 1971 THE Chemical Engineering graduate students formally requested a graduate level course in pollution control. From 1971 through 1973, Tulsa University conducted a M.S. level, EPA-sponsored program of training of engineers in oil-related water pollution control. This program created a need for a graduate course which would familiarize B.S. chemical engineers with industrial pollution control practices and design procedures.

Since 1974 the ChE Department has administered the University of Tulsa Environmental Protection (UTEPP) program—a non-profit, cooperative, petroleum industry-sponsored research program committed to studying present and future environmental protection problems in petroleum and related industries. Obviously, students working in UTEPP also require graduate-level instruction in industrial pollution control.

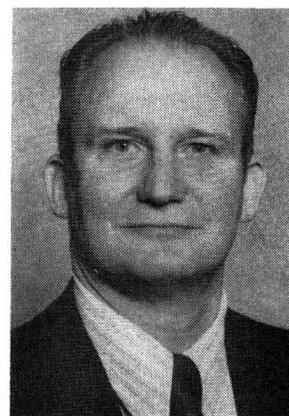
### COURSE OBJECTIVES

**I**NDUSTRIAL POLLUTION CONTROL not only focuses on the general theories of industrial pollution control to provide breadth of understanding, but also emphasizes petroleum-related design examples to provide the required specialization. Current industrial pollution control practices and design procedures are introduced as painlessly as possible. This is accomplished by emphasizing the relevancy of conventional, undergraduate chemical engineering. In other words, biological oxidation processes are described as chemical reactors; but, of course, new concepts such as the inherently varying wastewater “feed” volume and concentration and the sensitivity of “bugs” to shock loads are carefully described. Similarly, ammonia stripping is discussed using standard ChE desorption nomencla-

ture; and liquid condensation in pressure-relief lines is treated as a standard thermodynamic “flash calculation.”

### TEACHING FORMAT

**W**HILE THE TRADITIONAL lecture format is maintained, formal lecturing is minimized. For the past two years “Industrial Pollution Control” was taught via the Oklahoma Higher Education Televised Instruction System (Philon, 1974) thus allowing engineers from Conoco in Ponca City and Phillips Petroleum in Bartlesville to participate. This televised procedure permitted maximum use of class time because an overhead TV camera made it possible to project printed pages on the TV receiving screens. This minimized the timeconsuming writing of notes on the blackboard and the laborious copying by students. While two texts were recommended (but not required) the majority of the course material was selected from recent articles (see references for a partial listing). The references must be updated every year because of the great current interest in this field. Frequently students were



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supplied with reprints of key articles not readily available in the library.

Because "Industrial Pollution Control" covered such a wide range of topics, expert guest lecturers were used:—e.g. Paul Buthod for petroleum refining; Erle Donaldson for subsurface disposal; Dick Martin for noise control and Robert Reed for combustion and incineration. Plant trips to Sun Oil Company's Tulsa refinery and to William Brothers Analytical Laboratory were included.

Since 1970, the University of Tulsa has sponsored ten one-week short courses for industry on wastewater and air pollution control as applied to petroleum refining and related petrochemicals. These short courses have featured many nationally-known authorities such as Milton Beychok, Frank Bodurtha, Marion Buercklin, Lee Byers, Burton Crocker, Wes Eckenfelder, Davis Ford, Bill Licht, Leon Myers, Robert Reed, George Reid, Jim Seebold and others. Students enrolled in "Industrial Pollution Control" have always been encouraged to attend these short courses (free of charge) and were given complimentary notes for the short course. These short courses have enriched "Industrial Pollution Control" immeasurably. Last fall, for example, the students attended 35 hours of lectures on air pollution control and received approximately 200 pages of notes and design case histories. In-class treatment of air pollution then consisted of discussing points of student uncertainty and working extra problems.

Students were graded on 1) their solutions to the design problems; 2) two "term-papers" or more comprehensive design projects; and 3) their in-class presentation and defense of their design projects.

#### **COURSE OUTLINE**

• **Petroleum Refining** (1 hr lecture) A brief discussion of refining with emphasis on unit processing steps and the major sources and types of wastes is conducted. The chief concept presented is: increased processing is accompanied by increased production of potential pollutants. Nelson (1968).

• **Refinery Wastewater Treatment** (1 hr lecture) A brief summary is given of major uses of process water in a refinery emphasizing current recycling of process water and methods of minimizing volume of wastewater produced. Advantages of segregated sewers. Overview of primary, second-

ary, and tertiary treatment with emphasis on arrangement of treatment steps. Manning (1973).

• **Characterization of Industrial Wastewaters** (1 hr lecture) The problem of describing a wastewater in terms of a relatively few, standard analyses such as BOD, COD, TOC, SS, etc., is explained. FWPCA (1967).

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**The course not only focuses on the general theories of industrial pollution control to provide breadth of understanding; but also emphasizes petroleum-related design examples to provide the required specialization. Current industrial pollution control practices and design procedures are introduced by emphasizing the relevancy of conventional undergraduate ChE.**

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• **Biological Treatment** (2 weeks, 3 problems) Biological phenomena and related importance in understanding biological waste treatment are presented. Laboratory methods for modeling aerobic growth kinetics. Current design methods for sizing activated sludge and aerated lagoons including treatability studies, common start-up and operating problems and solutions, effluent qualities typically realized, and economic aspects. API (1969); Eckenfelder and Krenkel (1972); Thackston and Eckenfelder (1972); Adams and Eckenfelder (1974).

• **Sludge Handling** (1 week; 1 problem) Sludge handling is discussed in depth with emphasis upon alternative methods—sludge conditioning, thickening, dewatering, drying and digesting. Ultimate disposal methods such as land farming and landfill were reviewed. Dick (1972); Eckenfelder and Krenkel (1972).

• **Pretreatment** (2 weeks, 3 problems) The role of pretreatment on the operation of biological treatment such as activated sludge or aerated lagoons is discussed. Detailed design procedures for equalization basins; neutralization; oil separators (API and CPI); and dissolved air flotation units. Adams and Eckenfelder (1974); Ford and Manning (1974).

• **Tertiary Treatment** (1 week, 2 problems) Biological nitrification—denitrification are reviewed. Carbon adsorption and mixed-media filtration as effluent polishing steps are discussed. Emphasis is placed on the implications of EPA effluent criteria on the selection of processes, design procedures, and effluent qualities obtainable in industrial operation. Adams and Eckenfelder

(1974); Thackston and Eckenfelder (1974).

- **Subsurface Disposal** (1 hr lecture) The design and operation of underground disposal wells is reviewed including geology; economics; and the pros and cons of subsurface versus surface treatment. Donaldson (1974).
- **Water Quality Standards** (1hr lecture) BPCTCA: BATEA: new source standards and 1985 "Zero Discharge" regulations are reviewed, while emphasizing their effect on current treatment practices. Federal Register (1974).
- **Source and Ambient Air Sampling** (1 hr lecture) Procedures for stack sampling of particulates and gaseous procedures are reviewed with emphasis upon relevant case histories—isokinetic procedures for particulates, and analysis of SO<sub>2</sub>, NOX and hydrocarbons. Crocker and Schnelle (1970); Hesketh (1972).
- **Meteorology** (2 weeks, 3 problems) Fundamentals of meteorology are presented, including mixing processes; DALR; atmospheric stability; Pasquill and Turner's classifications; dispersion models using Gaussian models; plume rise. Design case histories are used to illustrate calculation procedures, including variations in ground-level concentration, time averaging, multiple stacks, etc. Crocker and Schnelle (1970); Schnelle and Noll (1972); Hesketh (1972).
- **Removal of Particulates** (2 weeks, 3 problems) The basic design criteria for particulate control with emphasis upon fundamental principles and mechanisms are reviewed. These principles are used to develop basic collector models, determine effects of dust size distributions, energy requirements, and optimal design criteria. Inertial separators (cyclones), filters, electrostatic precipitators, and wet scrubbers are included. Crocker and Schnelle (1970); Byers and Licht (1974); Hesketh (1972).
- **Control of SO<sub>2</sub> Emissions** (1 week) Control of SO<sub>2</sub> emissions from combustion and process gasses by limestone/dolomite injection, limestone and MgO slurry scrubbing, catalytic oxidation and alkaline scrubbing, and Claus recovery plants are discussed. Byers and Licht (1972).
- **Incineration** (2 weeks, 3 problems) Combustion fundamentals are reviewed, including fuel characteristics, fuel: air ratio, combustion temperature, heat transfer and mixing effects, effect of water vapor, heating value of fuels, speed of combustion, odor control by incineration and design methods for fluid bed and atomized suspension incinerators and for flares. Reed, R. D.

(1973); Eckenfelder and Krenkel (1972).

- **Hydrocarbon Losses; NOX Reduction** (1 hour lecture, 1 problem) Methods of controlling NOX emissions such as low excess air firing, staged combustion, flue gas recirculation, and inert injection are reviewed. Sarofin and Bartok (1973).
- **In-Plant Noise Control** (1 week, 1 problem) An introduction to the nature of noise, health aspects, pollution economics, major national sources, main concepts of in-plant noise (design versus external treatment), inplant noise legislation and basic physics of noise generation is presented. Kannapell and Seebold (1975).
- **Air Standards, Environmental Impact Studies** (1 lecture) We review federal legislation including the Clean Air Act of 1970, establishment of national air quality standards, implementation plans and emission standards for new and existing sources. Environmental Impact Statements are discussed. Beychok (1973); Hesketh (1972).

#### TYPICAL PROBLEMS

THE MAJORITY OF CLASS TIME is spent discussing design problems which are carefully formulated to reflect actual engineering practice. The students are not required to memorize typical operating conditions; but, hopefully they develop such engineering judgment by working with realistic numbers. These problems illustrate how the student's basic ChE knowledge can be applied to pollution control. This teaching philosophy is illustrated below in typical problems.

- **Biological Treatment** In addition to designing activated sludge and aerated lagoons by conventional methods (Adams and Eckenfelder, 1974) the students fit laboratory treatability data with 3 variations of the first order kinetics: thus discovering the empirical nature of the assumed kinetics. Also, if time permits, the students compare Beychok's (1970) data on aerated lagoons with plug-flow and perfectly-mixed reactor models. They are surprised to find that both models can fit the biological degradation data over the limited variation in residence time, etc. (Soper et al, 1975).
- **Neutralization** Students plot the daily amounts of base required to neutralize an acid coke and chemicals wastewater (pH=2.5) on probability paper. They test whether the daily requirements are normally distributed and learn what is meant by designing for the 90 or 95 percentile.

• **Equalization** Students plot the daily COD load from a typical (but hypothetical) refinery on probability paper. They then design an equalization basin using Novotny and Englande's (1974) method which assumes random fluctuations. Class discussion compares the results of the Novotny and Englande method with a rigorous, numerical, computer solution. This shows how a major spill produces a non-Gaussian distribution, and also indicates when Novotny and Englande's method should and should not be applied.

signment is to criticize a very misleading paper.

• **Sludge Incineration** This incineration design includes complete mass and energy balances; sizing combustion volume for a specified residence time; and specifying insulation. Sludge atomization using steam is examined.

#### ACKNOWLEDGMENTS

This course "Industrial Pollution Control" was made possible only by the advice, support,

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For the past two years "Industrial Pollution Control" was taught via the Oklahoma Higher Education Televised Instruction System—thus allowing engineers from Conoco in Ponca City and Phillips Petroleum in Bartlesville to participate. This televised procedure made it possible to project printed pages on the TV receiving screens.

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• **Stripping** Students first reconcile the design equations listed by Smith (Thackston and Eckenfelder, 1972, p. 140) with the standard ChE formulations for counter-current columns. They examine the relative magnitudes of the gas and liquid phase resistances. Finally the overwhelming effect of temperature on the feasibility of stripping is illustrated by sizing several towers. If time permits, Beychok's approach to high temperature, stripping of  $H_2S-NH_3$  mixtures is discussed (API, 1969, revised chapter).

• **Atmospheric Dispersion** Dispersion of  $SO_2$  is estimated using the Pasquill and Turner approach. The estimates are repeated for multiple stacks and at least two plume-rise formulae. Finally the differences between continuous point sources, and instantaneous "puff" sources are illustrated not by dwelling on the mathematical derivations but by working suitable examples. Students estimate the dispersion coefficients thus emphasizing the uncertainties inherent in the final answers. If time permits, students estimate the ground concentration of  $H_2S$  and/or mercaptan produced by releasing  $H_2S$  and/or mercaptan from a safety release valve. The resulting ground concentrations are then compared with odor thresholds and EPA air quality standards.

• **Flare Stack** The design of a flare stack includes estimating potential carbon escape, steam demand for smoke suppression; sizing storage space for liquid knock-out facility; ground-level radiant heat fluxes. Wherever possible students are introduced to alternative (and sometimes contradictory) design rules-of-thumb. In fact one as-

and contributions of many students, faculty, including adjuncts, industrial friends, and short-course lecturers. The author regrets that space limitations prevent individual recognition; but special thanks are due Marion Buercklin (Sun Oil Company) and Leon Meyers (E. P. A.) for serving as "founding fathers." □

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- (Continued on page 186.)

# SEPARATION PROCESSES: Particulate Systems And Column Operations

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**C**HEMICAL ENGINEERING 260 and 261 at UC Davis are each one quarter courses designed to introduce graduate students (and some seniors) to separation processes of particulate systems and column or cascade systems. Some students consider the courses as featuring applications of mass transfer, others, applications of mathematics. Some students hope to gain a deeper understanding for design of ChE unit operations, others desire a suitable background in a particular area so they may begin research or understand the research of others. In addition to these separate objectives the instructor hopes students in the courses are instilled with an appreciation for the interaction and interdependence of these subjects: mathematics, transport phenomena, design, and research.

Tables I and II show typical outlines of topics and lectures. These courses are not meant to overlap with other engineering courses at UC Davis, and therefore certain items are omitted that are adequately covered in the other courses. For the first course, a course in transport phenomena such as Section III in Bird, Stewart, and Lightfoot [1], is pre-requisite; for the second, an additional pre-requisite is a course in staged mass transfer operations.

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**Some students consider the courses as featuring applications of mass transfer; others, applications of mathematics. Some hope to gain a deeper understanding for design of ChE unit operations, others desire a suitable background in a particular area so they can begin research or understand the research of others.**

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TABLE I

## Outline of topics for ChE 260, Separation Processes: Particulate Systems

1. Membrane separations: colloid systems, reverse osmosis and ultrafiltration, problem of concentration polarization.
2. Distribution functions, population balances, moment equations.
3. Micro organisms; enzyme kinetics.
4. Birth, death, and fission kinetics.
5. Chemostat analysis: fermentation, activated sludge, sterilization.
6. Crystallization, nucleation, zone refining.
7. Liquid-liquid systems: particle agglomeration and breakage.
8. Aerosol dynamics: Knudsen, transition, continuum regimes.
9. Molecular velocity distribution functions, kinetic equations, hydrodynamic equations, constitutive equations.
10. Drag and thermal forces on aerosols; precipitators.
11. Evaporation and growth of aerosols.

## PARTICULATE SYSTEMS

**B**RIEFLY, THE FIRST COURSE is an analysis of particulate systems in, for example, pollution abatement and chemical process equipment. Macromolecules, micro-organisms, colloids, crystals, and aerosols are discussed. Population balances and distribution functions are mathematical concepts that tie the topics together and help maintain continuity. Variations of the classic ChE models, the plug flow and continuous stirred tank reactors, recur frequently as well.

Usually ChE 260 begins with the membrane separations: reverse osmosis (hyper filtration), ultrafiltration, dialysis, etc. The students inspect various membrane devices, and thermodynamics of osmotic pressure is reviewed (e.g. van't Hoff equation). Flux equations for solvent or solute transfer through the membrane are based on principles of irreversible thermodynamics. The



Benjamin J. McCoy received his B.S. degree from the Illinois Institute of Technology, and M.S. and Ph.D. degrees from the University of Minnesota (1967). He is presently an associate professor of chemical engineering at the University of California, Davis. His research interests are in rarefied gas phenomena, molecular theory of chemical kinetics, enzyme engineering, and separation processes.

role of concentration polarization is emphasized, and the film theory with rejection efficiency is introduced. We review correlations for mass transfer coefficients in various configurations for laminar and turbulent flow. For example, we show the Leveque model provides an analytical path to the laminar-flow form of the relation between Sherwood and Peclet numbers and the diameter to length ratio [2]:

$$Sh \propto Pe^{1/3} (d/x)^{1/3}$$

Techniques for increasing mass transfer and decreasing concentration polarization are discussed [3], including the effect of heating [4] and of pulsed operation [5]. For dewatering of certain food materials, the fluid is non-Newtonian. Thus the effect of the power law stress relation on transfer coefficients is studied [6]. For a mathematically more detailed description of the convective mass transfer in concentration polarization, the partial differential equations are written and solved by separation of variables [7]. The velocity profiles for the convective model are provided by the perturbation solution of the Navier-Stokes equation for the stream function [8].

Enzymes are macromolecules (proteins) that can be concentrated by ultra-filtration [9]. Their catalytic properties are first described by Michaelis-Menten kinetics, derived via the Briggs-Haldane model [10]. Expressions for conversion of substrate in plug flow, batch and continuous stirred tank reactors are compared. Rate equations for various competitive reactions, as well as methods of data analyses, are developed.

Various immobilized-enzyme reactors are compared. Rate equations for various competitive reactions, as well as methods of data analyses, are developed. Various immobilized-enzyme reactors are analyzed: for example, the differential equation for steady state diffusion and reaction of substrate in a porous spherical particle is solved for zeroth and first order kinetics due to an enzyme attached to the pore surfaces. Effectiveness factors are used to determine conversion for packed bed and slurry reactors of these porous particles [11].

Solubility and stability of proteins and colloids are discussed in terms of the electrical double layer [12]. The Debye-Huckel theory, which makes use of diffusion-like differential equations for electrostatic potential, is reviewed for the activity coefficients of dissolved enzymes [13]. The equilibrium theory of protein solubility shows how dissolved protein concentration depends on ionic strength [14]. Recent developments in affinity

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**The first course is an analysis of particulate systems in, for example, pollution abatement and chemical process equipment. Macromolecules, micro-organisms, colloids, crystals and aerosols are discussed. Population balances and distribution functions are mathematical concepts that tie the topics together and help maintain continuity.**

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chromatography to separate proteins are interpreted in terms of protein solubility in salt solutions [15].

Microencapsulated enzyme is an example of the simplest model of a microorganism. Substrate diffuses through the encapsulating membrane to react with the entrapped enzyme. Monod kinetics for bacterial growth follow naturally, and are used to derive equations for the operation of the steady state chemostat. Brief mention is made of the chemostat's relation to fermentation, activated sludge, and sterilization processes. The diffusion field in and around a single spherical cell is studied for zeroth and first order approximations to Michaelis-Menten kinetics inside the cell [16].

## POPULATION BALANCE

**T**HE COMPACT SECTION in Himmelblau and Bischoff [17] is followed closely to introduce and use population balance equations. A general

Reynolds transport theorem is used in this context, and the population balance equation is shown to be a generalization of the more familiar multicomponent mass balance. Moment equations are derived from the equation for the population distribution function. A macroscopic equation for the average distribution is shown to have obvious similarities with macroscopic equations in transport phenomena. The chemostat model for bacteria with time dependent mass is considered for special forms of birth, death, and fission terms. We briefly touch on problems of particle agglomeration and breakage in liquid-liquid systems.

Crystallizer product size distributions for the "mixed suspension, mixed product removal" model are discussed. Reading from the book on particulate processes by Randolph and Larson [18] is recommended. The basic picture of homogeneous nucleation with free energy depending on embryo size provides for a discussion of effects of supersaturation, interfacial tension, and critical cluster diameter [19]. We also discuss a model of zone refining [20].

The final major section of ChE 260 is based on rarefied gas transport phenomena and aerosol systems. First, the three rarefied gas regimes are defined: the Knudsen, transition, and continuum regimes with, respectively, the mean free path  $\lambda$  much greater than, about the same as, or much less than the characteristic geometrical length  $L$ , e.g., the particle diameter. We note qualitatively different phenomena are exhibited in the extreme regimes, but that a gradual transition bridges between regimes of other phenomena, e.g. phase changes, or laminar-turbulent transition. All this is to emphasize physical laws have limits: mathematical equations fail to describe physical reality outside the range of the model's application.

Because it appears in so many contexts, the equation for flux of molecules to a surface in free-molecule (Knudsen) flow is carefully developed.

$$j = p/\sqrt{2\pi mkT}$$

This equation is related to effusion, catalyst pore diffusion, the Knudsen vapor pressure cell, thermal transpiration, and deposition and evaporation at the surface of a particle—all processes in the Knudsen regime. Condensation and accommodation coefficients are defined. Knudsen regime formulas for heat transfer from a sphere, and for drag on a sphere are presented (reference is made to Kogan's book [21] for details).

The continuum gas regime is next treated, where intermolecular collisions dominate entirely over molecule/wall collisions. The Boltzmann kinetic equation is shown to have the same general form as population balance equations. The velocity distribution function has moments related to the observable mass density, velocity, and temperature of the gas. The moment equations are the point (hydrodynamic) equations of change. We introduce the simple relaxation (Krook) form of the intermolecular collision operator [22] and use the Chapman-Enskog technique to derive Newton's law of stress with viscosity coefficient,

$$\mu_c = \tau_c p$$

and Fourier's law of heat conduction with thermal conductivity coefficient,

$$\kappa_c = \frac{5}{2} \frac{k}{m} \tau_c p$$

in terms of the collision time  $\tau_c$ , pressure  $p$ , molecular mass  $m$ , and Boltzmann's constant  $k$ . The subscript  $c$  indicates the continuum limit.

We treat the transition regime by assuming that the collision frequency is the sum of collision frequencies of molecule/wall and molecule/molecule collisions [23]:

$$\frac{1}{\tau} = \frac{1}{\tau_K} + \frac{1}{\tau_c}$$

Such a hypothesis leads to transport coefficients obeying a well-known expression; e.g. for the viscosity,

$$\frac{1}{\mu} = \frac{1}{\mu_K} + \frac{1}{\mu_c}$$

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**The second course concerns the analysis and design of separation processes in columns or cascaded systems: distillation, leaching, extraction, adsorption, chromatography, absorption. Applied mathematics is a prominent aspect of the course including finite difference equations, probability and random walk theories, method of characteristics, and moment analysis.**

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Expressions for fluxes  $\Phi$  are usually of prime importance; we show that

$$\Phi/\Phi_c = \frac{1}{1 + GK}$$

where  $K = \lambda/L$  is the Knudsen number, and  $G$  depends on geometry and molecular accommodation. Further,

$$GK = \Phi_c/\Phi_K = \mu_c/\mu_K = \tau_c/\tau_K$$

TABLE II

Outline of topics for ChE 261,  
Separation Processes: Column Operations

1. Finite difference equations applied to staged operations: distillation, extraction, leaching, absorption. Derivation of Smoker, Fenske, and Kremser equations.
2. Rate processes in column operations: transfer unit analysis and unified design method for continuous contactors.
3. Axial dispersion: Taylor, random walk, other models.
4. Equilibrium theory of chromatography: binomial, Poisson, and Gaussian probability functions.
5. Breakthrough curve analysis: Goldstein J-function, Parex process.
6. Method of characteristics for solving first-order partial differential equations: chromatography, parametric pumping.
7. Moment analysis of pulse response experiments: adsorption, gas-liquid partition, gel permeation chromatography. Hermite polynomial representation of elution curves.
8. Chromatography resolution and optimization.

so that quite simple formulas describe the transition regime, formulas that are easily constructed if one knows the continuum and Knudsen flux expressions [23]. Transition range formulas are developed for heat and mass transport near a sphere, and drag on a sphere. The well-known Maxwell equation for evaporation or growth of a droplet is derived for simultaneous heat and mass transport [24]. Remarkably, when transition range diffusion and heat conductivity coefficients are inserted into the Maxwell formula, one obtains precisely the same equation derived by Fukuta and Walters [24] by quite a different approach.

### COLUMN OPERATIONS

THE SECOND COURSE concerns the analysis and design of separation processes in columns or cascaded systems: distillation, leaching, extraction, adsorption, chromatography, absorption. Applied mathematics is a prominent aspect of the course, including finite difference equations, probability and random walk theories, method of characteristics, and moment analysis via Laplace transformation. The emphasis is on mathematics as a reflection of the physical world, and the usefulness (or necessity) of the derived equations for design of equipment is continually noted. The

students in ChE 261 are asked to purchase King's *Separation Processes* [25], from which numerous reading and problem assignments are made.

We begin with the calculus of finite differences applied to staged units [26]. Analytical methods for solving difference equations are compared to methods for differential equations. Murphrey efficiencies are included in the analysis of systems whose equilibrium can be described by a linear relation or by a constant separation factor (relative volatility). The Smoker, Fenske, and Kremser equations are derived, and a host of problems of industrial interest are solved for homework.

Depending on the interests of the students, we have sometimes treated multicomponent distillation for constant relative volatility systems. Here, matrix methods and computer techniques are discussed [24].

We review the analysis of two-phase separations controlled by interphase mass transfer when longitudinal dispersion can be ignored [1]. The resulting expression for number of transfer units (NTU) is related to height equivalent to a theoretical stage (HETP).

Descriptive notions of longitudinal dispersion in columns are introduced. The Danckwerts boundary conditions for a finite-length column are derived following the simple, yet general treatment by Bischoff [28]. A unified design method for continuous-contact mass transfer operations unifies a large class of operations with dispersion [29].

Following Feller [30], we introduce the probability concepts of binomial distribution and Bernoulli trials. The Poisson and normal Gaussian distributions are treated as approximations to the binomial distributions. The first and second moments of the three distributions are derived and compared.

We follow King's treatment [25] of the intermittent carrier flow model for equilibrium stages, to get the binomial distribution of solute among stages. We use a generating function method [30] to obtain the Poisson distribution solution to the difference-differential equation for the continuous-flow equilibrium-stage model of chromatographic separators. From the Gaussian approximation we extend this analysis to develop the relations for the equilibrium model of chromatography. We also use the generating function method to analyze a breakthrough curve for a cascade of equilibrium stages.

One-dimensional random walk theory is used

in the conventional manner to derive the diffusion equation,

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} .$$

A solution for a delta function initial condition is derived by means of the gaussian approximation to the binomial distribution [31]. This solution is used as a Green's function to get superposition solutions for several other initial conditions [32]. This material is then related to the convected dispersion problem in a tube, and conditions for the Peclet number are derived under which a chromatographic output curve is gaussian with respect to time [33]. Related topics, such as Fourier transform solutions, Brownian motion, and the Einstein formula for diffusion coefficients, have been dealt with in some years, depending on available time and student interest.

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**There is considerable interest . . . in using dynamic response methods (e.g. pulse response) to quantify parameters in a range of systems: packed-bed and slurry catalytic reactors, kidneys, distillation columns, chicken lungs, etc.**

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## TREATMENT OF DISPERSION

**W**E NEXT TREAT dispersion in a more thorough manner by means of the Taylor-Aris model via the moment analysis of convection and diffusion [34]. Some other models and correlations of data are discussed [35-39].

The Goldstein J-function solution for the non-dispersed first order partial differential equations for breakthrough curves is derived by Laplace transforms [40]. The discussion of this model and the graphical presentation of the solution by Hougen and Watson [41] is noted. The application to the Parex adsorption process for recovering p-xylene from its mixtures with other C<sub>8</sub> hydrocarbons is discussed [42]. We also consider ion exchange processes.

The method of characteristics is also useful for time-dependent problems when diffusion effects can be ignored. Simple chromatography [35] and parametric pumping [43] are analyzed by this method.

There is considerable interest in our department in using dynamic response methods (e.g.

pulse response) to quantify parameters in a range of systems: packed-bed and slurry catalytic reactors, kidneys, distillation columns, chicken lungs, etc. The method is introduced by a pulse response analysis of an open tube; for the concentration  $c(t,x)$  we have

$$\frac{\partial c}{\partial t} = -v \frac{\partial c}{\partial x} + D \frac{\partial^2 c}{\partial x^2} .$$

The equation is Laplace transformed, and the resulting ordinary differential equation is solved for  $c(s,x)$ . From the definition of the transformed concentration,  $c(s,x)$ , we prove that

$$\lim_{s \rightarrow 0} \frac{d^k c}{ds^k} = (-1)^k \int_0^{\infty} t^k c dt,$$

where the integral is the kth moment. Therefore, we can take limits of derivatives of the solution,  $c(s,x)$ , to relate the statistical moments to the parameters of the system. The moments may be calculated from experimental response data, and parameters evaluated. The technique is extended to breakthrough curve analysis (response to a step function input), and to frequency analysis (response to a sinusoidal input).

Considerable effort is put into the moment treatment of adsorption chromatography [44], of which (gel) permeation chromatography is the special case when adsorption is negligible. Adsorption (or a linear chemical reaction) may occur at the pore surfaces of porous particles in packed columns. Pore diffusion, interparticle mass transfer, and axial dispersion all play a role. Expressions of moments and methods of getting information out of pulse response data are presented [45, 46].

Since an output pulse is often nearly gaussian, hermite polynomials are defined and used to reconstruct the output curve in terms of moments, and thus in terms of system parameters [47]. For the separation of two solutes with gaussian outputs, a resolution criterion is defined for their separation, and optimization with regard to column length and operating velocity is discussed [48]. This approach has the advantage that considerable semi-empirical knowledge can be organized by one comprehensive method. The optimization is extended to apply to product value, and equipment and operating costs [48]. We point out the same methods can be applied to capillary chromatography or partition chromatography.

. . . students in the  
**courses are instilled with an appreciation for  
the interaction and interdependence of mathematics,  
transport phenomena, design, and research. . . . The  
emphasis is on mathematics as a reflection of the  
physical world, and the usefulness of the derived  
equations for design of equipment  
is continually noted.**

## CONCLUDING REMARKS

**O**UR EXPERIENCE INDICATES considerable material can be covered in the two 30-lecture quarters if tedious algebraic manipulations on the blackboard are kept to a minimum. Such manipulations are often assigned as homework so students may gain familiarity with the mathematical symbols and their meaning in terms of the physical world. Lecture notes are frequently xeroxed and handed out, so lectures emphasize concepts and conclusions. Many of the papers referenced here are assigned reading, to bring students up to the frontiers of research. □

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## ADMINISTRATION OF ENGINEERING AND TECHNICAL PERSONNEL

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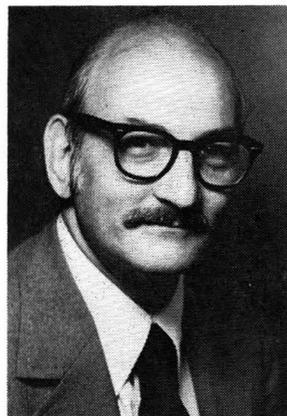
**E**NGINEERS ARE TRAINED to deal with objective things—with variables that are governed by physical laws. Many of us were in fact attracted to engineering because of the elegant predictability of the material and scientific world. The slide rule was our trademark, and now the pocket electronic calculator permits multi-digit precision in our calculations. But when it comes to matters involving people, we enter into a non-calculable, subjective, often unpredictable world. If it is governed by laws at all, these are largely unknown, and certainly have little to do with logic. Rather, the world of people is characterized by wide individual differences, and by unquantifiable and emotional factors seemingly designed to make engineers uncomfortable.

Surely, we are largely untrained in these matters. Yet engineers are people, they do have feelings, and they do behave unpredictably, just like other people.

Also, whether they like it or not, engineers encounter human problems all the time; certainly they do in their employment situations. Further, if they are managers, their professional success depends in large measure on their human relations skills. Yet most engineers have not had a day's training in dealing with "people" problems. But that's where the action is, and that's where the opportunities for the future are. So that's why we feel it's appropriate to give some attention to this important side of engineering training, and offer this introductory course.

Consider the following:

- We can send men to the moon, but we haven't learned to solve the traffic problems in our cities and on our campuses.
- We know how to build a nuclear power plant—but we don't know whether to build them.



Professor Polack has been Head of the Chemical Engineering Department at L. S. U. since 1970. After receiving the Sc.D. from M. I. T. in 1948, he spent 22 years with the Exxon Corporation in a variety of technical and managerial posts. From 1966 to 1970, he was Director of the Esso Research Laboratories (now Exxon Research and Development Laboratories) in Baton Rouge.

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- We know how to drill for offshore oil, but not whether to drill for it.
  - We come up with a slick solution to a technical problem, but we are unable to persuade our bosses to implement it.

The successful engineer of tomorrow must learn to deal with these human problems. The fact of the matter is that many, if not most, engineers reach the peak of their technical sophistication while they are in school. Only a small percentage (primarily those who remain in academe) will ever be faced with problems as technically difficult as those given in a typical Ph.D. qualifying exam. But most will face very perplexing human, management and political problems that they are poorly equipped to deal with.

### INTRODUCING MANAGEMENT

**A** MAJOR PURPOSE of this graduate course is to introduce the engineer to the human and organizational problems of the manager and

to give some hints as to how these problems might be approached. Another important purpose of the course is to introduce the engineer to the body of knowledge which exists in the field of management and human relations. There *are* principles of management, even if they seem to be proven as much by exception as by rule. Surely they are inexact in comparison to the laws of science. What is hoped is that this introduction will capture the interest of the students so that they will continue to read in the management and human relations areas. There is definitive literature in the field and it is an appropriate subject for scholarly study, rudimentary though the science of management may be. Finally, the course provides some opportunity for the student to gain some knowledge of self and others by his participation in the case discussions which take up the bulk of the classroom time.

#### COURSE ORGANIZATION

**T**HE COURSE IS DESIGNED to proceed from the familiar to the less familiar. At the start, we discuss what a business is, and what impact management's philosophy has on its conduct. From this we proceed to look at various models of organizational structure from the simple pyramid to modern matrix or multi-dimensional structures. Some of the principles of organizational theory, i.e., the concepts of span of control, unity of command, and delegation of authority are described; and case studies bring out the human problems and frustrations which arise from misunderstanding of these theories and philosophical concepts.

The next block of study has to do with motivation, morale, and leadership. Research findings of Mayo, Maslow, McGregor and others are used as basis for understanding a wide variety of human conflicts and problems. Here, too, case histories, drawn from the literature as well as the experience of the instructor, provide the material for classroom work. Both individual and group interactions are studied.

Finally, attention is centered on specific management activities including communications, counselling, performance appraisal, training and the like. A detailed outline is shown in Table I.

#### CASE STUDY FORMAT

**T**HE STUDENT IS expected to do outside reading and also prepares a term paper, discussed further below. The class period itself (one and a half hours twice a week) is given over almost exclusively to discussion. The lecture technique is

**TABLE I**  
**Abbreviated Outline of Course**

- A. Introduction
  - Management as a Profession
  - Philosophies of Management
- B. Organizational Structures; Theory and Practice
  - Functional, Federal, Matrix Structures, etc.
  - Traditional Principles of Organization: Span of Control, Unity of Command, etc.
  - Delegation of Authority
- C. Motivation and Leadership
  - Maslow's Hierarchy of Needs
  - McGregor's Theory X and Theory Y
  - Development of Participation
  - Management of Change
- D. Group Processes and Social Environments
  - The Individual in the Organization
  - Scientific and Technical Employees
  - 1st Line Supervision
  - Communications Processes
  - Appraisal and Incentives
- E. Overview: Factors in Above Outline all Interact Simultaneously. So the Sequence Shown is one of Convenience Rather than Logic.

rarely used, except for an occasional guest lecture on a special topic. The reason is that the specific factual information covered is easily obtained by the student from his textbook and other sources. To learn about human relations and problems involving people, one must experience the differences of opinion and feelings that can arise. This is best done through classroom discussion, role playing and other experiential techniques. The case method is the principal study method used in this course. During the semester, fifteen

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**When it comes to matters involving people, we enter into a non-calculable, subjective, often unpredictable world. If it is governed by laws at all, these are largely unknown, and certainly have little to do with logic. Rather, the world of people is characterized by wide individual differences, and by unquantifiable and emotional factors seemingly designed to make engineers uncomfortable.**

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or twenty different cases are considered by the class.

Following are some examples of cases covered:

- A manager bypasses a supervisor and deals directly with a staff engineer on a rush job. As a result, foundations for a new compressor are poured before it is discovered that the compressor specified is not available. Strained relationships result among various organizational groups.
- The maintenance department reduces janitorial service. So the supervisor in an engineering group asks the secretary to dust the conference table and desks every day. Two weeks later, she resigns, stating that her husband has been transferred to another city. But several weeks after that, the supervisor sees her shopping in a local supermarket, and discovers that she has another local job.
- A small company, in which the president is in close contact with the first line supervisors, is extremely successful and expands rapidly. Mounting problems of production require that the president bring in a new plant manager and an efficiency expert. Midnight one Saturday night the front line supervisors storm into the president's office, demanding that he get rid of the new supervisory employees.

The above vignettes are of necessity quite abbreviated, as the cases include much more detail. In the classroom discussion, each person is encouraged to express his view on the situation presented. It is quite amazing to hear the many different views that are brought forth on what seem to be simple problems—but aren't. The role of the instructor is to keep the discussion open in order to generate as many options as possible, and then to aid the students in seeing advantages and disadvantages of different approaches.

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**A major purpose . . . is to introduce the engineer to the human problems of the manager and to give some hints as to how these problems might be approached . . . and to introduce the engineer to the body of knowledge . . . in the field of management and human relations.**

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In human relations problems, there are no "right" answers. What we try to develop is either approaches and/or solutions which can lead to better outcomes for all participants in a situation. The underlying thesis is that by working the "people" problems, the manager then makes it possible for individuals to work the "work" problems. (Too often, we tend to work the technical problems and ignore the "people" problems.)

## WRITING, SPEAKING AND READING

**E**ACH STUDENT WRITES a term paper which accounts for about 40% of his grade. A variety of topics are suggested, but the students are free to select topics of their own. Many of them do.

**TABLE II**  
**Typical Term Paper Topics**

Motivation and Creativity  
The Informal Organization  
Elimination of Job Boredom  
Group Dynamics—T Groups  
Management of a Non-Profit Organization  
Conformity  
Communications Problems in Large Organizations  
Organization of a National Pizza Chain  
Appraising Personnel Performance

Table II lists some of the titles students have selected in recent years. The student is expected to make full use of the literature. He is encouraged to express his own opinions, but must document what he says with examples and/or reference to authority. Performance of students on these papers varies, depending largely on the amount of time they spend. Sometimes, a student gets deeply interested in a subject and does a spectacularly good job. For example, one student did a study on creativity, which itself was most creative and, in the instructor's opinion, worthy of being the starting point for some substantial original work. Some students who are industrially employed make studies of their own company organizations, using the insights they have gained from the course. If the class is small enough, the students give oral reports on their term papers.

While guest speakers are not extensively used, speakers from the Psychology and Speech departments have been quite effective in lecturing and leading discussions on communications and human interactions. Such speakers introduce variety and help to give the students an appreciation of the talent available in the university community in fields other than engineering.

The textbook used is "Human Behavior at Work" subtitled "Human Relations and Organizational Behavior" by Keith Davis (McGraw-Hill, 4th edition, 1972). There are many texts dealing with this subject and the choice is a matter of the individual instructor's preference. All of the texts basically cover the same material (just like

various texts on thermodynamics). I like the Davis text because it is comprehensive, the material is well documented, and it is written in a readable, interesting way. Also, each chapter has case studies for use in class, and there is an excellent collection of cases which comprise the appendix to the book.

In addition, the students are given a reading list (see Table III) and are encouraged to read on their own. To keep them honest, they are quizzed on certain specific reading assignments during the term. The reading list is liberally supplemented by reprints of articles from journals such as the Harvard Business Review.

### THE STUDENTS

ONLY GRADUATE STUDENTS may take this course. Many are part-time students who are currently employed by local industry. By offering the course in the early evening, we make it easy for such students to attend after work. This is an ideal group of students. Having experienced some of the vicissitudes of industrial organizational life, they readily recognize the reality of the case studies. They are eager to participate in the discussions, for they feel that the material is directly relevant to their day-to-day work. The students learn from each other, and the instructor learns from them, too. Most of the full-time students have usually had at least summer employment in industry, and they, too, take an active part. On the other hand, it is somewhat more difficult for a totally inexperienced student to participate in and thereby benefit from the course.

My own feeling is that **undergraduates** could benefit by some exposure to this subject matter.

TABLE III

#### Excerpts from Reading List

- Drucker, P.—The Practice of Management  
The Concept of the Corporation  
McGregor, D.—The Human Side of the Enterprise  
Greenewalt, C.—The Uncommon Man  
Argyris, C.—Personality and Organization  
Likert, R.—New Patterns in Management  
The Human Organization  
Whyte, W. H.—The Organization Man  
The Harvard Business Review  
Publications of the American Management Association

However, for undergraduates, I would recommend a different course design—one which would thrust the student into an experiential situation. Some sort of simulation of a real work problem would, I think, be necessary for the student to really appreciate the feelings which are engendered in such situations.

### SUMMARY

In summary, the major challenges facing the engineer of tomorrow are as much nontechnical as technical. This course introduces the engineering graduate student to the body of knowledge which exists in the management and human relations field and hopefully provides him with some insight into dealing with problems in these important areas. People have a tremendous potential for achievement, and the modern corporation is a remarkable device for accomplishment of high purposes. Progressive managers concentrate on helping people to fulfill their own aims and to achieve a greater proportion of their potential. In this way, organizational achievement can be maximized. □

## ChE book reviews

### Fundamentals and Modeling of Separation Processes, Absorption, Distillation, Evaporation, and Extraction.

By Charles D. Holland  
Prentice-Hall. 430 pages.

Reviewed by Verle N. Schrod, Monsanto Agricultural Products Company.

When asked to review this book I agreed to do so without remembering that I had reviewed another of Dr. Holland's books some 11 or 12 years ago. This previous work, "Unsteady State Processes with Applications in Multicomponent Distillation" was quite good but had a somewhat misleading title since it was only concerned with distillation. I thought perhaps this one would be equally good and would really cover other processes and would be fun to read so I went ahead with the review.

The book was a pleasure to read. It covers the fundamentals of the four named basic separations

(Continued on page 191.)

## TECHNOLOGICAL FORECASTING

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**T**HE FULL TITLE of the course is "Technological Forecasting: An Aid to Decision Making." It is a one trimester course (13 weeks) offered to graduate students in engineering and open to extension service students. The existence of this course reflects our view of the technological age for which we are training graduate engineers. That view accepts the role of the engineer in industry, business or in the public service, as an expert technologist, as a prime agent for technological innovation, for technology transfer from pilot to full production scale, and so on. It also recognizes that we live in an era of unprecedented concern for the husbanding of natural resources, for the protection of public and environmental safety and for the economic and societal consequences of technology and its spreading use. Further, it considers the engineering graduate and more particularly the holder of Masters or Doctoral degrees as a decision maker who will function in that capacity at a very early stage of a professional career. It is no longer reasonable however, to make decisions on technological matters without taking into account the possible economic, societal, environmental and political motivations for these decisions and in turn, the impact of the decisions on these inter-related factors. Our course is designed to introduce the graduate engineer to the complex interactions between technological and the non-technological factors noted above and to create in him an awareness of the complex crossimpacts which must be weighed in the decision-making process. In short, we hope to give him a balanced preparation for the complex roles which he will in all probability, be asked to perform in the course of a professional career.

The growing discipline of technological fore-

casting (TF) appears to offer a suitable vehicle for coping with the intellectual problems outlined above. In recent years TF has become a staple of planning groups in business and government. Such professional organizations as the Hudson Institute, the Stanford Research Institute, Boston Consulting Group, etc. have become widely recognized spokesmen for the importance of this planning aid. Though far from a precise discipline, TF has now taken on some aspects of analytic science (1-8) and has been the subject of training courses offered mainly to executives in industry and government. We believe there is a need in the graduate engineering curriculum for a view of this evolving discipline, in a version which stresses the analytic concepts of data analysis and trend extrapolation, and which particularly stresses application of TF methods to situations relevant to regional and national needs touching upon technology. We are not alone in this belief; to give a few examples, J. H. Hallomon, of M.I.T.'s Center for Policy Alternatives, has recently urged universities to act as focal points for the development of skills in technological planning, technology assessment and in evaluating the impact of technology on those who should use it (9). The widening concern in Engineering faculties over the functions and power of Technology Assessment offices, has led to Symposia on this complex topic (10). To the best of our knowledge, however, our just-completed exposure (winter 1975) of the TF course makes the first formal appearance of this "soft" discipline in an approved curriculum.

### COURSE CONTENT

The TF course is divided into three main sections and a complementary fourth part:

**Background:** In this first three-week segment, the philosophic basis for planning disciplines is laid down. Mathematical principles of data analysis, elements of probability functions and

games theory are introduced. Particular stress is laid on the character of linear and exponential growth. Examples of the latter mode were drawn from the Club of Rome Study on the Limits of Growth (11).

**The Tools of TF:** The second segment (four weeks) is devoted to a consideration of major practical approaches to the technological planning function. Intuitive, heuristic and normative methods of forecasting are outlined. Major approaches considered in detail include:

- trend extrapolation
- Delphi interrogation
- structured interview
- relevance tree construction
- substitution theory
- input, output tabulation
- scenario writing

As a course guide here, we have used J. R. Bright's *A Brief Introduction to Technology Forecasting* (Pemaquid Press, Austin Texas, 1972), but emphasis was placed in case histories drawn from published reports of Institutes such as Stanford Research, Battelle, etc.

**TF & Planning Workshop:** The third and major portion of the course is 6 weeks long with additional consultation sessions arranged between instructors and students. The students were divided into working teams (5-6 individuals per team), each team selecting a topic on which they would develop a scenario depicting the future technological status (5-10 years away) of the industry relating to the topic. The scenario had to consider various non-technological options, such as a surprise-free future, major changes in political, environmental or social attitudes toward a given section of technology, the resource base from which the industries must operate, etc. A major need was to identify threats to opportunities for existing technology and innovative technology respectively, and to identify events in the forecast span which could be used as signals as to the validity (or non-validity) of the planning forecast. The completed scenario was used as the solo source for determining each student's standing in the course.

**Supplementary Lectures:** A group of lectures (four in the 1975 term) given by invited senior spokesmen from industries and governments, dealing with special aspects of technology planning, its management, transfer and assessment, complemented the formal content of the course.

Though inevitably only loosely interconnected, the lectures served their purpose in providing insight into the role of technology and of the engineer in various occupational spheres and at various career stages.

## INITIAL COURSE EVALUATION

**WE ARE UNDER NO** illusion as to the hazards involved in presenting a course of this type to engineering students, and as to the difficulty in deciding on the content and methods of presenting the material. We have much to learn, but are pleased with the response obtained in our first year of operation.

It was evident that the engineering students (about 2/3 of a total of 23—the remainder had backgrounds in economics and business administration) initially approached the subject with misgivings and were distinctly cool about the ultimate value of the course to their fund of knowledge. Matters began to change noticeably in the second portion of the course; the case

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**Our view of the technological age recognizes we live in an era of unprecedented concern for husbanding natural resources, for the protection of public and environmental safety and for the economic and societal consequences of technology and its spreading use.**

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examples involved here ranged from "classical" illustrations of substitution theory (steamship technology replacing sail, jet engines replacing piston plants, etc.) to analyses and extrapolations of the development of computer technology, and Delphi-based statements on the future competition between audio-visual communication methods and public transportation (both long and short distance). In each of these examples, further evidence was presented to support the thesis that technological growth patterns can be categorized, that to some degree the technology of the future can be planned for and controlled. Consequently, the students began to comprehend their role as future coordinators of the multidisciplinary pressures upon and arising from their activities in the technological sphere.

The work-shop section was enthusiastically accomplished, notwithstanding the fact that the average time input far exceeded the formally

scheduled period of 18 hours. Scenarios were produced on:

- Evolution of steel-making technology (1975-2000)
- The competitive balance between the steel and plastics industry in 1985.
- Plastics recycle technology in 1985.

The final results lack the authority and balanced viewpoints of professional reports. They are by no means academic exercises, however, and have provided some interesting insights into the future stance of industries important to the regional and national economies. Beyond any doubt the authors have a truer view of the nature of these industries and of the environment in which they will probably be operating during the students' working careers. We believe that as a result of this training, this group may accommodate more quickly to the realities of the industrial and business worlds; and thus make their presence felt to their benefit and to the benefit of society in general. □

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Continued from page 173.

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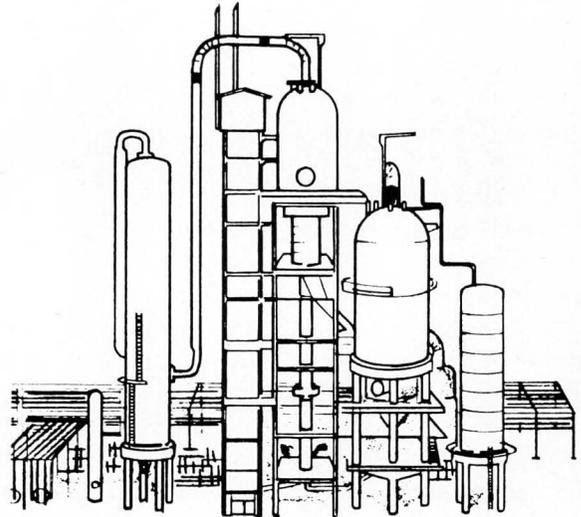
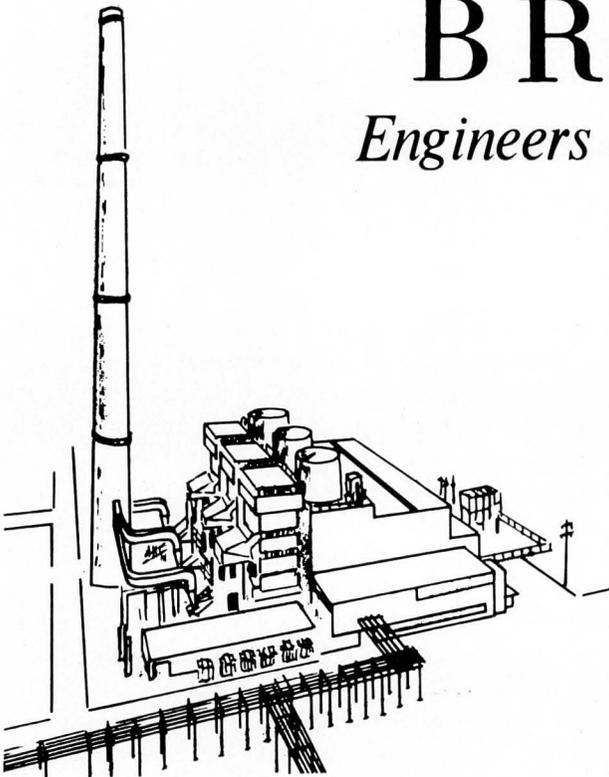
H. P. Schreiber graduated with B.Sc. and M.Sc. degrees from the University of Manitoba and obtained his Ph.D. at the University of Toronto. Following post-doctoral work at N.R.C. Ottawa, he joined Canadian Industries Ltd. in 1955, and served until 1973 as research chemist, Research Scientist and Group Leader, concentrating on polymer. He is Professor of ChE Ecole Polytechnique. Dr. Rigaud is a graduate of Ecole Polytechnique, Montreal, and holds bachelors, masters and Ph.D. degrees from that Institution in metallurgical engineering. Until 1974 Chairman of the Metallurgical Engineering Department, he is currently Associate Director for Research at Sidbec-Dosco, Contrecoeur.

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## ENZYME CATALYSIS

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**A**T FIRST GLANCE it surprises enzymologists that enzymes are not utilized much more widely in batch chemical engineering processes. This attitude comes from the enzymologists' creed: "Enzymes will catalyze virtually any chemical reaction, and they will do it better than any other catalyst."

At second glance, however, the surprise is gone. The problems associated with using enzyme technology in chemical engineering processes are immense: They range from the lack of education about enzymes amongst chemical engineers and the lack of education and interest about ChE applications among enzymologists, to the severity of the problems well trained biochemical engineers must solve in order to keep enzymes happy in environments dictated by engineering considerations.

The apparently recent realization that the earth is a finite system has accelerated interest in waste treatment processes, solar energy utilization, clean-burning fuels, food technology, human population control, and environmental quality. Each of these important engineering problems is related in some way to biological (and therefore enzyme-catalyzed) processes. Biological degradation of waste is the oldest and still most widely-used process of waste disposal. The **sole** energy source in biology is the sun, so living systems are old hands at capturing and utilizing solar energy. Because micro-organisms have to co-exist with what they excrete, relatively clean burning fuels are the natural product of many biological fermentations. Food is a biological material so its manipulation and interconversion by enzyme-catalyzed processes is clearly involving obvious biological components.

For these and other reasons it became clear that the catalysis program in our department

should include a graduate level course about enzyme catalysis. We designed this course to provide engineers and students in the sciences with a basic understanding of how enzymes and multi-enzyme systems function as catalysts. Special emphasis is on enzyme specificity, efficiency and control, and how these characteristics relate to potential applications in biochemical engineering. The course is structured so that the student is exposed to: [1] basic concepts about enzymes and enzyme catalysis and [2] the methodologies of enzyme chemistry and enzyme kinetics.

The course is designed for first level graduate students in engineering, but senior-level undergraduate students in chemical engineering, chemistry, or the biological sciences, as well as graduate students in these sciences, and interested medical students are welcome to register. I would expect adequately prepared students in any of these categories to be able to do well in this course. Obviously, a knowledge of biochemistry

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**The enzymologist's creed: "Enzymes will catalyze virtually any chemical reaction, and they will do it better than any other catalyst."**

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and/or enzymology would be helpful, but it is not essential. The prerequisites listed for the course are calculus, physical chemistry, organic chemistry, and elementary computer programming. The principle reference material includes the following four books: *Enzyme Reactions and Enzyme Systems* [1], *Biochemical Regulatory Mechanisms in Eukaryotic Cells* [2], *Steady-state Applications in Enzyme Kinetics* [3], and *Immobilized Enzymes* [4].

### DISCUSSION OF COURSE MATERIAL

#### I. The Chemical Structure of Enzymes

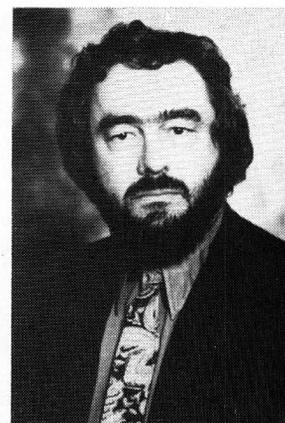
The purpose of this part of the course is to

introduce the student to basic concepts about enzyme structure and function.

The first section outlines the nomenclature recommended for enzymes in the 1961 Report of the Commission on Enzymes of the International Union of Biochemistry [5]. The second section provides the student with an understanding of the role in protein structure and enzyme activity of the peptide bond, other covalent bonds, hydrogen bonding, apolar associative forces, and other

**TABLE I**  
**Course Outline**

- I. The Chemical Structure of Enzymes
  - A. Enzyme nomenclature
  - B. Primary, secondary, tertiary and quaternary structure
  - C. The concept of the "active site"
  - D. The concept of the "regulatory site"
  - E. Cofactors
  - F. Control properties implicit in chemical structure
- II. Kinetic Properties of Single Enzymes in Solution
  - A. The general theory of enzyme kinetics, the law of mass action
  - B. Initial transient kinetics
  - C. The quasi-steady-state approximation and its validity in enzyme kinetics
  - D. Quasi-steady-state models
  - E. Near-equilibrium techniques and their kinetic analysis
  - F. Near-equilibrium versus quasi-steady-state tracer distribution kinetics
  - G. Simulation of enzyme models on analog and digital computers
  - H. Computer methods for generating rate equations for enzyme models
    - I. The collection and analysis of enzyme kinetic data with on-line computational facilities.
- III. Kinetic Properties of Multi-enzyme Systems
  - A. The general theory of control; applications in biochemical engineering
  - B. The theory of far-from-equilibrium systems; applications to multi-enzyme systems
  - C. Kinetics of multi-component systems without feedback control
  - D. Kinetics of multi-component systems with feedback control
  - E. Integrated reaction kinetics of enzyme reactors
  - F. Simultaneous reactors and diffusion in enzyme reactors
- IV. Immobilized Enzymes and Enzyme Systems
  - A. Types of support
  - B. Covalent coupling methods
  - C. Effects due to coupling on enzyme activity and other enzyme properties
  - D. Theoretical effects of immobilization on enzyme kinetics
  - E. Consideration of physical and diffusional constraints imposed by the carrier on enzyme catalysis



Charles F. Walter received his B.S. (1957), M.S. (1959), and Ph.D. (1962) degrees in chemistry at Florida State University. He was appointed Assistant Professor (1964) and Associate Professor (1968) of Biochemistry at the University of Tennessee Medical School in Memphis. In 1970 he was appointed Associate Professor of Biomathematics and Associate Professor of Biochemistry at the University of Texas System Cancer Center, M. D. Anderson Hospital and Tumor Institute in Houston. In 1974 Dr. Walter was appointed to his present position as Professor of Chemical Engineering at the University of Houston. His research and teaching interests include enzymology applied to biochemical engineering problems in hydrogen generation from cellulose, the chemistry of nucleotide-nucleotide.

non-covalent interactions. Section C, about the catalytic sites of enzymes, emphasizes current ideas about the indigenous nature of certain sites on enzyme surfaces, and how sites not indigenous on the enzyme surface can be induced by the proximity of a ligand (usually the substrate) to the site area. Similarly, Section D, which is about regulatory binding sites on enzymes, emphasizes current concepts about how these noncatalytic sites, when associated with specific ligand molecules, interact with catalytic sites and thereby alter catalytic activity. General models involving cooperative interactions between regulatory and catalytic sites and stimulation or inhibition of catalytic behavior are emphasized [6, 7]. Section E deals with the role of cofactors in the induction of non-indigenous substrate binding sites, and the last section is about the type of control of catalytic activity that is "built in" by the primary, second, tertiary, and quaternary structure of enzymes.

## II. Kinetic Properties of Single Enzymes in Solution

The purpose of this part of the course is to provide the students with a fundamental understanding of the kinetics and control properties of single isolated enzymes in homogenous solutions.

The first section reviews the law of mass action and its applications to enzyme models. The overall chemical reaction, the development of empirical kinetic equations for enzyme-catalyzed reactions, the relation between these kinetic equations and initial rate equations, and a description

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**The apparently recent realization that the earth is a finite system has accelerated interest in waste treatment processes, solar energy utilization, cleanburning fuels, food technology, human population control and environmental quality. Each of these . . . is related in some way to biological (and therefore enzyme-catalyzed) processes.**

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of a general initial quasi-steady-state rate equation for multisubstrate enzyme models are included in Section A. The second section is about the kinetic behavior of enzyme-catalyzed reactions prior to the attainment of a quasi-steady-state. Section C includes a rigorous discussion of the concept of a quasi-steady-state in a closed system, and a derivation of the relationship between the error introduced by using the quasi-steady-state approximation, the magnitude of the kinetic constants for the enzyme, and the experimental initial conditions used. Section D is a review of quasi-steady-state enzyme models, the use of the King and Altman algorithm [8] to derive them, and the relationship between these approximate mathematical models and the real chemical mechanisms they approximate. Sections E and F are about the relaxation kinetics of enzyme reactions that have been perturbed slightly from thermodynamic equilibrium. Perturbation techniques that are discussed include stepwise temperature changes, periodic pressure variations, and the addition of small quantities of a radioactively labelled reactant. In section F the usefulness of kinetic experiments involving the addition of traces of labelled reactant to an enzyme and its reactants near thermodynamic equilibrium, and kinetic experiments wherein large quantities of labelled substrate are added to an enzyme and its reactants far from equilibrium, is compared. Section G is about the simulation of enzyme models on analog computers, and their numerical "simulation" on digital machines. For the digital simulations we have chosen the program by Chance, Shephard and Curtis, "The

University College London Enzyme Simulator" [9]. This program is especially easy to use because it "automatically" translates the individual chemical steps into mathematical relationships via a built-in equation translator routine. Section H explains the use of a computer program [10, 11] that uses the King and Altman [8] algorithm to derive quasi-steady-state rate equations for any enzyme model. The last section of this part is a description of how enzyme kinetic data is properly analyzed. This section includes a comparison of the graphical and "standard" statistical procedures usually employed in the analysis of enzyme rates, a discussion of one-line methods for the collection and analysis of data from enzyme-catalyzed reactions, a critical evaluation of integrated forms of quasi-steady-state rate equations, and the use of experimental data and digital computer programs like "The University College London Enzyme Simulator" [9] to estimate individual rate constants in assumed enzyme models.

### III. Kinetic Properties of Multi-enzyme Systems

The purpose of this part of the course is to provide the students with a comprehensive understanding of the kinetics and control properties of a sequence of enzyme-catalyzed reactions in a homogeneous solution.

The first section reviews the general theory of control for linear and nonlinear systems. Application of the Lyapunov direct method to biological control systems of interest in biochemical engineering is illustrated, and the existence and significance of limit cycles in biochemical systems is discussed. The next section is about the theory of far-from-equilibrium chemical systems; dissipative structures and the spatial and temporal organization of such systems are discussed from the point of view of the rich organizational behavior implicit in the nonlinear partial differential equations that describe them. Sections C and D are about the dynamics, stability, and control properties of nonlinear multi-chemical systems with or without feedback control; emphasis in these sections is on multi-enzyme systems with negative feedback of the Yates and Pardee [12] type, or positive feedback of the type thought to be responsible for the limit cycle concentration oscillations of the components in the glycolytic pathway [13, 14]. Analysis of the stability properties of these control systems is carried out with the aid of: [1] the usual analysis for

linearized systems [15, 16]; [2] perturbation theory; [3] the Aisermann conjecture [17]; [4] the Lur's transformation and algorithm for obtaining a global Lyapunov function [18]; and [5] computer simulations of the nonlinear differential equations [19, 20]. The analysis of the control properties is carried out by comparing the sensitivity of metabolic levels of the components in the models to parameter variations. The last two sections are about applications of the theory of enzyme kinetics and control to chemical reactor processes. Section E deals with situations where diffusion is not important, and Section F with examples where the effects of diffusion must be included in the differential equations describing the enzyme-catalyzed reactions in the reactor.

#### IV. Immobilized Enzymes and Enzyme Systems

The purpose of the last part of the course is to acquaint students with heterogeneous enzyme catalysis and its role in problems in biochemical engineering.

The first two sections review the various types of supports and covalent coupling methods used to bind enzymes. Section C is about the effects of immobilization methods on enzyme structure, and especially on those aspects of structure changes which effect enzyme activity via modification of the active site and/or control sites. This section introduces the student to possible effects of these structural modifications on the overall kinetics of the immobilized enzymes. The next section compares the kinetics of homogeneous and heterogeneous enzymes or enzyme systems. The last section examines the physical and diffusional constraints imposed on enzymes or multi-enzyme systems by immobilization. □

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#### BOOK REVIEW

Continued from page 183.

processes and the treatment is thorough and complete and certainly not elementary. The fundamentals are covered in 5 chapters in Section I and then in Section II two chapters are devoted to modeling and rate process fundamentals followed by 5 chapters on adsorption, distillation and extraction. In these chapters several different models are proposed and then selected ones are used to model actual field results for industrial columns. For example a packed distillation column 34 ft. high and containing 9260 lbs. of Pall Rings is modeled in detail as is a packed extractor 72 ft. high and 5 ft. in diameter handling 12,000 barrels of kerosene per day. There are other examples for plate towers. The results appear to be uniformly good. Calculated and experimental product compositions agree well over wide variations in the input parameters.

The book should be useful in a senior or graduate level design course. There are numerous problems and plenty of references. If very much use was to be made of the techniques, access to a computer would be needed for solving sets of equations for separations involving many components and many plates. The book should also be useful to industrial designers although I would think that most would already be familiar with the methods in this book since the techniques have been published in various journals and theses. □

# CRITICAL PATH PLANNING OF GRADUATE RESEARCH

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**T**HE CRITICAL PATH method (CPM) has proven to be exceptionally beneficial over the last fifteen years for the control of project operations, and for task planning and control in many industries. In addition to its proven success in industry, the critical path method has been applied successfully in the education educational sphere for the planning of ChE curricula [1]. The vast majority of the literature on CPM concerns applications requiring computer solution of the critical path by parametric, linear programming [2], whereas non-computer methods are needed for the routine application of this method in small laboratory research projects. In this paper, a simplified procedure is presented for applying the critical path method to graduate research programs, using noncomputerized techniques readily available to the student. Recent experience with the method is drawn from several graduate-level ChE research programs.

## TWO DIFFERENT FORMS

**T**HE BASIC CONCEPTS of critical path planning were initially developed in two fundamentally different forms. The "probabilistic" approach was known as Program Evaluation of Research Tasks (PERT) or PERT with costs (PERTCO) [3]. In this form, individual research and development tasks, whose duration and cost could not be accurately estimated, were assigned a range of probable duration and cost. These

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**The critical path method is applied to graduate research programs . . . Experience shows a high correlation between task identification and effective task completion by the student.**

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**TABLE I. Steps in the Critical Path Method**

Phase I.	Project decomposition into a realistic network of task sequences. A. Assignment of individual tasks. B. Estimate of times and cost benefits. C. Construction of a precedence—contribution matrix. D. Assignments of topical sequences.
Phase II.	Critical path determination for a normal project rate. A. Construction of an arrow diagram. B. Determination of the critical path.
Phase III.	Time-cost-benefit optimization A. Estimation of times and cost-benefits for highest rate. B. Calculation of incremental cost slopes. C. Determination of the critical path.

data were then incorporated into a computerized critical-path control program. A second form of CPM, called Project Planning and Scheduling System (PPSS), was predicated on a more deterministic approach, where the controlling variables of individual tasks are assumed to be estimated with reasonable accuracy [4]. The latter approach has been utilized effectively in the chemical and construction industries [4, 5]. The deterministic approach is more suitable for graduate research planning provided that the controlling variables can be quantitatively assessed.

## NONCOMPUTER CPM

**T**HERE ARE THREE important phases of the CPM method developed here for graduate research. These are summarized in Table I. In the first phase, the overall project is divided into distinct tasks. It is useful to divide long project operations into a sequence of separate tasks. The tasks are then ordered into topical sequences with the aid of a precedence-contribution matrix: each task follows its precedents, but should come before tasks to which it contributes. An arrow diagram is then constructed from which the critical path is determined, again using informa-

tion in the precedence-contribution matrix. The program is finally optimized by calculating the incremental cost-benefits per unit of time saved, for alternative forms of the project tasks.

The noncomputer critical path method proposed for graduate research planning is perhaps best illustrated with an example. Consider a typical set of research tasks arising in a project having both analytical and experimental components. Following the steps listed in Table I, one first lists the individual tasks of the project and assigns values of the time required and the cost-benefit to each, as shown in the left-hand part of Table II. Dead times requiring no work input are separately listed. Next, a precedence-contribution matrix is constructed, as shown in Table III, where the precedent steps are identified, as are subsequent steps which benefit from each step. The information on precedents is then used to construct the topical sequences shown in Table III. Here, for example, task 2 is listed following task 1 in sequence because task 1 is a precedent, whereas task 3 is placed at the start of a new sequence because no precedent step is required. All duplicate tasks numbers in this table could be deleted to simplify the table.

The second phase of the method is the determination of the critical path for a normal project rate. For this, an arrow diagram is first constructed from the information in Tables III and IV, with arrows connecting each step to its required precedent steps, as shown by the solid lines in Fig. 1a. Then, Table II is examined to determine the first subsequent step to which a given step contributes. These contributions are denoted by the dotted lines in Fig. 1a.

It is evident from Fig. 1a that task 3 could precede task 1, but there is no clear precedence requirement. It is appropriate, therefore, to further subdivide task 1 into two parts, where one

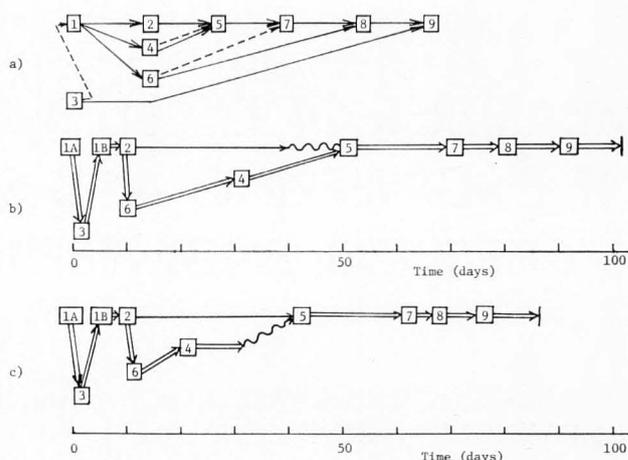


FIGURE 1. Task sequencing of a typical graduate research program: a) arrow diagram, b) critical path for a normal program rate, c) critical path for an accelerated rate.

part requires task 3 as a precedent. Note also, that several tasks are in parallel (i.e., 2, 4 and 6) and could be performed by a large work force. The graduate student constitutes a one-man crew, however, and therefore an addition criterion must be supplied to determine the task sequence. Two criteria are proposed here: (i) Table II is examined for each task in a parallel group (i.e., 2, 4 and 6). The number of contribution entries in the column for each is counted, and the task with the highest number of "C" entries is performed first. Alternately, (ii) the parallel tasks should be further subdivided and ordered so that the graduate student alternates his time between them, thereby gaining experience with all the tasks early in the program. Following criterion (i), one can readily arrive at the critical path program shown in Fig. 1b for the normal program rate. The critical path is denoted by double arrows, while idle time durations are denoted by wavy arrows (e.g., for task 2).

(Continued on page 203.)

TABLE II. Time, Cost and Cost-Slope Estimates for a Typical Project

Task	Task Name	Normal Rate		Accelerated Rate		Incremental Cost Slope (\$/d)
		Time (d)	Cost-Benefit (\$)	Time (d)	Cost-Benefit (\$)	
1	Define Problem	5	100	5	100	$\infty$
2	Order Supplies	30*	520	30	520	$\infty$
3	Lit. Survey	5	100	5	100	$\infty$
4	Construct App.	20	1000	10	2000	100
5	Experimental	20	400	20	400	$\infty$
6	Analyt. Calc.	20	700	10	1000	150
7	Data Reduction	10	200	5	200	0
8	Compare Theo & Exp.	10	200	10	200	$\infty$
9	Write Reports	10	200	10	200	$\infty$

\*29 day dead time.

# MEASURES OF EXCELLENCE OF ENGINEERING AND SCIENCE DEPARTMENTS: A CHEMICAL ENGINEERING EXAMPLE

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**T**HE PURPOSE OF this study was to determine how such measures<sup>1</sup> of departmental and research quality as number of citations of current research papers, number of citations of the research of a lifetime, number of Ph.D.'s graduated, funds expended for research, number of papers published, and others, correlate with one another and with the quality or visibility of departments as measured by peer evaluations such as those conducted by Cartter [1] and more recently by Roose and Andersen [2]. The number of citations by others correlates best with the other measures in the present study.

Numerous studies of citation analysis have been reported relatively recently [3, 4, 5, 6, 7, 8]. Also, the Institute for Scientific Information (ISI)

has conducted a citation study for the National Science Foundation of all professors in the 78 leading chemistry departments listed in the Roose-Andersen report [2]. Several questions arise regarding the use of citations as measures of the quality of the research of an individual or group. First, does the number of citations provide a reasonably valid measure of research quality? Second, should one be concerned primarily with citations of recent work or of the work of a lifetime in assessing the value of the contributions that one has the potential for making in the future? Third, do citation counts correlate with other measures of quality, both objective and subjective? Fourth, can one compare the quality of individuals or groups in different disciplines on the basis of citation counts?

In the present study a simple random sample of 21 departments of chemical engineering in the U.S. universities was selected. Citations were counted in the *Science Citation Index* (SCI) (11)

TABLE 1

Spearman Rank Order Intercorrelation Coefficients for Departments of Chemical Engineering  
N = Number of Departments Correlated in the Measure

No.	N	Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	21	Citations by others		.99	.95	.93	.91	.87	.85	.82	.87	.74	.81	.76	.63	.50	.31
2	21	Total citations			.95	.93	.87	.84	.81	.87	.72	.83	.74	.62	.47	.27	
3	21	Citations/professor				.89	.87	.82	.79	.71	.79	.83	.82	.68	.60	.42	.32
4	21	Papers with 5-9 citations					.93	.84	.86	.71	.71	.71	.73	.74	.42	.30	.10
5	21	Self-citations						.82	.86	.79	.57	.71	.69	.77	.40	.36	.16
6	21	Lifetime citations							.70	.59	.78	.54	.79	.57	.65	.48	.25
7	21	Number of papers								.67	.65	.84	.44	.94	.17	.43	.25
8	17	Research expenditures									.77	.59	.58	.65	.58	.45	.28
9	9	Papers with 10+ citations										.50	.72	.49	.56	.29	.13
10	12	Papers/professor											.42	.78	.15	.38	.36
11	21	Citations/paper												.30	.66	.27	.19
12	21	Papers with 0-4 citations													-.02	.44	.22
13	16	1970 Rating of Graduate Programs														.58	.58
14	21	Ph.D.'s graduated															.93
15	21	Ph.D.'s./professor															

for 1965-9 (cumulative), 1970, 1971, and through June of 1972. The departments were ranked by number of citations, etc., and the rankings were compared with the unpublished Roose-Andersen rankings (that were supplied by Andersen) by use of the Spearman rank-order intercorrelation coefficients between all pairs of rankings. Results are in Table 1. All correlations are significant at least at the five percent level of confidence.

## RESEARCH CITATIONS

**T**HE NUMBERS OF citations to research by professors in different ChE departments varies much more than do other measures. In the 21 departments studied, the average number of lifetime citations<sup>1</sup> per professor varied in different departments from 275 in one department to 8 in another department with a mean of 79 for all professors in all departments; average number of citations<sup>1</sup> of 1967-9 articles per professor varied from 40 to 0.9 with a mean of 13 per department; number of papers published per professor in different departments varied from 6.5 to 0.63 with a mean of 3.6. The variation among individual professors is much greater than among departments. For example, lifetime citations vary from 0 to 1,100 and those of 1967-9 articles from 0 to 162. Thus, it seems that the recognition, as measured by the number of citations to works of professors in different departments, varies much more than does the rate at which they publish articles, and departments with professors who publish more, on the average, seem to be the source of work that is used (cited) more. These data dispel the myth that those who publish prolifically, publish less significant work; quantity and quality are correlated highly positively.

Our low correlation coefficient, 0.17, between the number of articles and peer recognition (Roose & Andersen (RA) study (2)) contrasts with the 0.67 obtained by Hagstrom [12] for biology, chemistry, mathematics, and physics departments. This suggests that there may be a difference, on the average, between the impact of science and applied science articles.

Departmental reputations as measured by the RA study [2], tend to correlate slightly better with lifetime citations than with '67-9 departmental citations.<sup>1</sup> That is, it is not only the work that is presently being done or has been done in the recent past, but also the work that has been done years ago, that contributes significantly to

the reputation among peers of individuals and departments. Our results show the correlation coefficient between peer judgment (RA) and the first-author citations to be 0.65; Hagstrom [12] obtained 0.69. Also, our results for both first-author lifetime citations and total '67-9 citations are 0.65 and 0.62, respectively; Hagstroms and our results are on the same order but are somewhat lower than the 0.75 obtained in the recent study of 78 leading chemistry departments carried out by ISI [13]. On the other hand, our correlation between citations per article and the RA ratings is 0.66 whereas the ISI correlation is only 0.48. The ISI counting by computer was the most comprehensive, ours was next, and Hagstrom's was the least since he apparently used first-author data for only 1966.

## CITATION OVERLAP

**W**E HAVE CONSIDERED essentially five different measures of excellence including various types of citation counts, research support,

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**We have considered essentially five different measures of excellence including various types of citation counts, research support, numbers of papers published, peer evaluations and Ph.D.'s produced.**

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numbers of papers published, peer evaluations and Ph.D.'s produced. Clearly, the various types of citation counts overlap in items counted and therefore high correlation coefficients between these counts are not surprising. The other four measures are not so obviously related to one another or to citation counts. Therefore, we might wish to ask which of the ways of counting citations has the highest mean correlation with the four non-citation measures. On this basis citations by others and total citations per department correlate most highly with the other measures (0.70 and 0.69) and these are followed by citations per professor (0.63).

It is somewhat surprising that number 15, Ph.D.'s graduated per professor has among the lowest correlation with the other measures. However, number 14, Ph.D.'s graduated per department, correlates quite well, on the same order as citation counts, with the peer evaluations of

**TABLE 2**  
**Data on Measures**

No.	MEASURE	MAXIMUM	MINIMUM	MEAN	MEDIAN
1	Citations by others/dept.	428	7	151	89
2	Total citations/dept.	495	7	179	111
3	Citations/professor	40	0.9	13.4	11.4
4	Papers with 5-9 citations	23	0	8.9	6
5	Self-citations/dept.	74	0	27.4	21
6	Lifetime citations/dept.	3,847	58	963	772
7	Number of papers/dept.	118	5	46.4	39
8	Research expenditures/yr.	\$664,K	\$28,K	\$265,K	\$251,K
9	Papers with 10-plus citations	18	1	8.1	7.5
10	Papers/professor	6.5	0	3.7	3.6
11	Citations/paper	6.9	1.1	3.3	2.9
12	Papers with 0-4 citations	75	4	28	21
13	Withheld				
14	Ph.D's. Graduated/yr.	12	1	4.4	4
15	Ph.D's./professor/yr.	0.93	0.09	0.36	0.30
16	Lifetime citations/professor	1,194	0	78.6	32.5
17	Professors/school	21	5	12.1	11

the Roose-Andersen 1970 Rating of Graduate Programs. This implies that department size is important and larger departments are more visible to others in the field.

Maxima, minima, means, and medians of the measures in Table 1, plus numbers 16 and 17, are given in Table II. It is interesting to note that, on a departmental basis, the citation counts per professor show means and medians that do not differ greatly. However, number 16 in Table II, which refers to the lifetime citations per individual, shows a mean of about 79 and a median of 33. This indicates that, on an individual basis,

the distribution of citations is highly skewed and that a relatively small number of highly talented people contribute work that is highly cited and which accounts for a large fraction of all of the citations of the entire group. Thus, the mean does not reflect the performance of the average individual because the average is so strongly influenced by those with outstanding citation records. The median seems much more representative of average individual performance.

It does not seem reasonable to compare the quality of departments in different disciplines by the measures discussed. For example, the average chemistry article is cited close to 10 times (one department was lowest with 5.3, another had 25.3 in the ISI study) whereas the average ChE article is cited about 3 times or less. Some data were obtained on various engineering departments to see if citation rates differ among them. It appears that civil and mechanical engineers cite somewhat less frequently (1/3 to 1/2) than do chemical engineers, and electrical engineers cite perhaps twice as frequently as do chemical engineers.

The relationship between age and productivity of chemical engineers is interesting. As shown in Figure 1, all measures of research productivity peak in the 40-44 age group; individuals in this group published an average of approximately 5 papers each during the two-year period, 1967-9, and these papers were cited approximately 5 times each; the lifetime citations for this group averaged about 126 per professor.

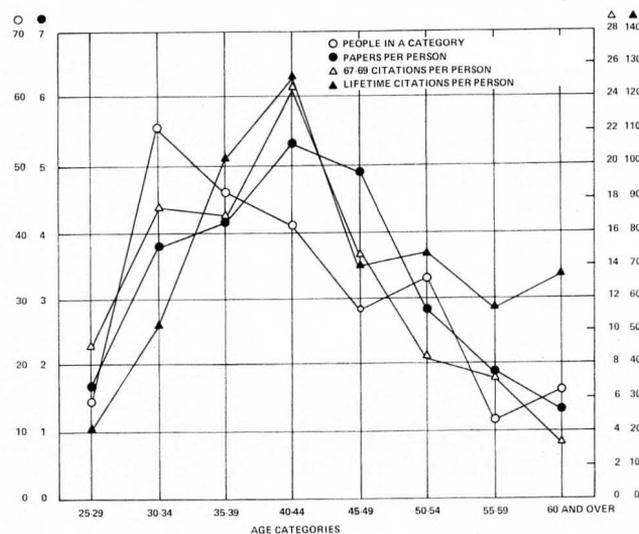


FIGURE 1

Relationship between age and productivity in Chemical Engineers.

## PERFORMANCE EVALUATION

**E**VALUATION OF THE performance of individuals and departments is difficult at best, but it is customary and necessary. Appointment, funding, promotion, ranking, selection, and tenure depend upon the results of evaluation. Objective data, such as those discussed here, are useful (if crude) measures that enable one to minimize unrealistic appraisals. It certainly seems that the number of citations should be included in any evaluation of the research performance of individuals or departments. Indeed, the dossier of every candidate for tenure or promotion should include a citation analysis of his published work.

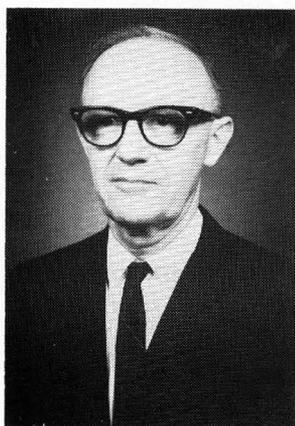
### DEFINITIONS

1. Citations by others: Number of non-self citations of works published between 1967 and 1969 and listed in the *American Chemical Society Directory of Graduate Research, 1971* [10] (including those works in

which the author studied is not listed first on the work). *Science Citation Indexes: 1965-9* cumulative, 1970, 1971, and the first half of 1972 were used for the random sample of 21 departments of chemical engineering in the U. S.

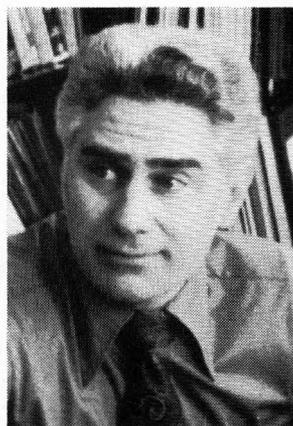
2. Total citations: Self-citations plus citations by others.
3. Citations/professor: Total citations of '67-9 works divided by number of faculty members.
4. Papers with 5-9 citations: Works published in the '67-9 period per department—with 5-9 total citations.
5. Self-citations: Authors' citations of their own '67-9 works (including those works on which their names do not appear first).
6. Lifetime citations: The number of citations, including self-citations, to all works on which a faculty member is first or only author.
7. Number of papers: Works published in the '67-9 period.
8. Research expenditures: Dollars spent per department for research per year, averaged for the '67-9 period.
9. Papers with 10-plus citations: Works published in

(Continued on page 202.)



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**William N. Gill** took his Ph.D. at Syracuse University and remained there on the faculty until 1965 at which time he joined the Department of Chemical Engineering at Clarkson College of Technology as Chairman. In 1971 he became Provost of the Faculty of Engineering and Applied Sciences and Professor of Chemical En-



gineering at the State University of New York at Buffalo. He has written about 100 articles on theoretical and experimental studies in transport phenomena. Recently his main research activities have been in reverse osmosis, including hollow fiber systems, and the development of a new theory of unsteady convective diffusion in which a generalized dispersion model is derived from first principles.

(CENTER)

**Raymond G. Hunt** is Director of the Survey Research Center, and is Faculty Professor of Social Sciences and Administration at the State University of New York at Buffalo. He received his Ph.D. from the University of Buffalo where he was formerly Professor of Social Psychology and chairman for Graduate Studies in the Department of Psychology. He has also served as Acting Director of the Social Science Research Institute at SUNYAB and was previously Professor in the Department of Community Service Education, College of Human Ecology, Cornell University. Professor Hunt is a Fellow of the American Psychological Association and a member of the American Sociological Association, the American Association for the Advancement of Sciences, the Association of Research Administrators, and the Academy of Management. He is author or co-author of four books and of numerous articles and papers. (RIGHT)

# SHOULD ENGINEERING STUDENTS BE TAUGHT TO BLOW THE WHISTLE ON INDUSTRY?\*

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**T**HE QUESTION to be answered is not only **should** an engineer blow the whistle on industry but whether students of engineering should be **taught** to do so. This leads to the broad question of whether moral or ethical standards of any kind should be **taught** to engineering students. Our answer is that we consider our students to be free individuals who must ultimately make their own choices based on their own sense of values. The teacher cannot play God; he cannot program them with a list of rules or a set of absolutes. What he **can** do, however, is to assist them in seeing the alternatives and to familiarize them with the way others have approached moral problems. The teacher can tell them how **he** might act in a given situation and he can make them conscious and aware of the **consequences** of moral decisions (or indecisions) but he should not and cannot make the decisions for them.

However, in order to give the student a basis for making his moral decisions we would present for his consideration the following hierarchy of moral values that have been proposed by the philosopher Robert Hartman:

- 1) **Extrinsic values:** These are basically material values, e.g. the monetary value of an automobile, a house, a boat, a heat exchanger, or of any material thing.
- 2) **Systemic values:** These deal with systems or organizations. Loyalty to an organization such as one's employer, to a fraternity, to a school, to a profession, to a department in a university, to one's country, or to a political system are systemic values.

\*Presented at the American Society for Engineering Education Annual Conference, June 25-28, 1973 Iowa State University Ames, Iowa 50010.

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Ray Fahien is professor of chemical engineering at the University of Florida and a former chairman of the department. He received his bachelor's in chemical engineering at Washington University (St. Louis), his master's at University of Missouri (Rolla) and his Ph.D. at Purdue. He has worked for Ethyl Corporation and has taught at Rolla, at Iowa State, at the University of Brazil, and at the University of Wisconsin. He is now on leave as a UNESCO consultant at the University of the Orient in Puerto La Cruz, Venezuela.

John C. Biery is Chairman and Professor of chemical engineering at the University of Florida. He received his bachelor's in chemical engineering at the University of Michigan and his Ph.D. at Iowa State University. He did postdoctoral work under Prof. R. B. Bird at the University of Wisconsin and has worked at Dow Chemical Co. and at Los Alamos Scientific Laboratory. He has taught at the University of Arizona and at Florida and is the author of papers on sodium technology, transport phenomena liquid-liquid extraction, and engineering education. He is a member of the ASEE Chemical Engineering Division Executive Committee, and chairman of the Motivational Techniques Session at the November 1975 AIChE meeting in Los Angeles.

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- 3) **Intrinsic values:** These might also be called human or spiritual values. They include the idea of the infinite worth and dignity of a human being. Intrinsic values cannot be measured in terms of dollars and cents. The highest of these values is that of an individual human life.

While systemic values are rated higher than extrinsic values, they are superseded by intrinsic values. Everything in the world, including the world itself, can be valued extrinsically, systemically, or intrinsically. For example, a button can be valued systemically as the product of a button factory, extrinsically as a useful part of a shirt, and intrinsically as an object to which a fetishist is devoted.

An engineering student can be valued systemically as another graduate or "product" of a department, extrinsically in comparison with other engineering students, and intrinsically in his own uniqueness as a human being.

Let us now apply these to some possible cases in which the engineer must make a moral decision. In each case we will presume that the financial welfare of the company is in jeopardy and that the engineer subscribes to the above hierarchy of values.

**Case I:** The company is releasing substances or manufactures a product that will **undoubtedly** result in death or serious injury; e.g. a **botulism**-causing bacteria in a canned good or the release of fluorides into the atmosphere. The engineer **must** "blow the whistle" because human life, an intrinsic value, is more important than the good of the company, a systemic value.

**Case II:** The company releases substances or manufactures a product that **may** result in death or serious injury. For example, his company is making flammable children's pajamas or labeling a combustible urethane foam as non-combustible. In this case the engineer must first decide whether a high probability of human death or injury actually does exist under the likely conditions of use. We feel that if such a risk is real he would be justified in informing consumer and governmental groups of the potential danger—assuming that he has done everything in his power to convince management of the problem.

**Case III:** The company is making a product that is to be used in a conflict that the engineer considers to be an "unjust" war. In this case the engineer should resign if his personal conscience tells him that he cannot work for a company that makes such a product. However, if there is a legitimate difference of opinion as to whether a war is or is not just, he should be cautious about inflicting his own moral concepts on others by publicly "blowing the whistle." On the other hand he might recall that Adolf Eichman, who burned thousands of Jews in ovens during World War II, claimed he was innocent because he was merely following orders and acting as a "transportation system". This is a good example of placing systemic values—presumably loyalty to the country—ahead of intrinsic values. The chemists and engineers who worked for the Krupp works in Nazi Germany undoubtedly also felt that their responsibility was only to the company and to their country.

**Case IV:** The company is releasing pollutants that the engineer **thinks** are deleterious to the environment, but which are not directly dangerous to humans. In this case, the company is probably, under today's legal atmosphere, already taking

steps to eliminate the problem. If so, the engineer should work within the company to accelerate the process. He should balance the good he can do in that manner against the good and harm he might do by "blowing the whistle". In this case both the good of the environment and the financial welfare of the company can be viewed intrinsically in terms of their effects on people. In the name of human values the environment must be protected, but also, in the name of human values, the role of the company in manufacturing a useful product and in providing employment to the community must be considered. Here each case must be decided separately, but loyalty to the company should not require them to defend a company that repeatedly despoils the environment.

**Case V:** The company is selling a product that is useless but is known to be harmless; e.g. a battery or crankcase additive, or an ineffective but harmless patent medicine. In this case he should honestly inform management of the results of any tests that he had made. If the product is then falsely advertised, he should leave the company.

## TWO SIDES OF THE COIN

We feel therefore that the engineer today should be aware that there are really two elements of the question of blowing the whistle on industry: One is the attempt to do it internally, to influence management in ways that are both beneficial to the company but which still satisfy the moral integrity of the engineer as he views himself and as he views his job in reference to the

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**While systematic values are rated higher than extrinsic values, they are superseded by intrinsic values. Everything in the world, including the world itself, can be valued extrinsically, systemically or intrinsically.**

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company and to the society about him. The second is to do something externally. We feel that this should be done if the first approach fails. Of course some may argue that the engineer who tries to accomplish change of this type internally is doomed to failure. While this may have been true in the past, we feel that the young

engineer who is leaving the university and entering industry today has a great opportunity, if he so wishes, to have an impact on the decision and management processes of his company. One possible reason for this increased influence is the teetering balance in which the companies find themselves between the problems of continued profitability and the pressure of (a) maintaining safety standards for OSHA, (b) in meeting pollution standards as prescribed by EPA, and (c) in meeting the demands of equal employment and non-discrimination as required by various federal laws and as expedited by the Department of Health, Education, and Welfare. From our point of view, one of our important jobs in education is to inform the engineer of his position of making his influence felt and known in the organization that he is joining.

We also think that at this time efforts in the direction of being immediately involved can have definite results. The trend in many management schemes is to try to drop the decision making process to the lowest possible level. One company (as we have been informed recently) is involved in such a program in which the lowest level of either management (or maybe non-management; i.e. the actual operating personnel) will make the decisions which they can make. They can influence their job each day and possibly even influence more than themselves; they may influence the organization in which they are working. In the experience of one of us at Los Alamos Scientific Laboratory, the decision making process was very much centered in the so-called staff member. He was not a member of management as such but actually the ideas for projects, the direction that projects were to proceed came in most cases from the staff member. We hope that our students will go out into the industry with the idea that they are a member of the management team and that they can contribute directly to the decision-making processes going on.

#### THE 9 TO 5 MAN

**I**N THIS DISCUSSION we have been influenced to a great extent by the book, **The Greening of America** by Reich. Many of his descriptions of human nature, of the types of Consciousness I, II, and III, from our own experience, are extremely accurate. These descriptions illustrate how most engineers perhaps have behaved in the past and how they possibly might behave in the fu-

ture. A good number of engineers are members of the Consciousness II group as described by Reich. This group is one that believes in large organizations, large structured groups. A Consciousness II engineer would believe that the decisions made by the organization are not to be challenged. He should go ahead and blindly do as

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**We feel that the young engineer who is leaving the university and entering industry today has a great opportunity, if he so wishes, to have an impact on the decision and management processes of his company.**

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he is told to do and don't worry about it. The attitude is: "Do your job; get your 40 hours a week in; and then forget about it. Let's get home, let's get to the beach, let's do our thing on the weekend, let's live a bifurcated life, a life which involves fun and family on one hand and the almost forced involvement with a company on the other."

If we educate students to go out into industry with the idea that this is the only possible point of view, we are making a great mistake. We are not priming our students or engineers to be the effective persons that they can be in industry.

With this view in mind we are teaching a seminar course at the University of Florida to seniors in which we are using **The Greening of America** and **Man, The Manipulator** by Shostrum as texts to look at the various stances that we as engineers can take. The question we've asked them is: "Can we take stances other than the classical one?" The classical one is being a member of Group II Consciousness. Is there a possibility of integrating some of the ideas of Group III consciousness into our engineering profession and into our ideas of achievement and still be strongly productive and interactive? In **Man, The Manipulator**, Shostrum describes the manipulative forms that many of us find ourselves trapped in but also describes the thrilling description of the actualized person: the person who really can be interactive, can be open, can express his feelings, can share and be intimately involved in the sharing and feedback process. Our hope is that our engineers can take on some of these actualized concepts.

## THE ACTUALIZED CONTRIBUTOR

**A** PERSON CERTAINLY HAS to have some of the concepts or elements of the actualized person to immediately contribute towards an organization. He must take risks. He must speak up. He must involve himself in a productive way with all the decisions in which he has contact. He has the difficulty of doing this in a way which is acceptable to the people around him. He cannot be overbearing; he makes no points that way. But he cannot be under-aggressive; he again makes no points. So, therefore, the process is one of sensing where the other human being is, being aware of where his managers are and of their capabilities and maybe lack of capabilities.

Therefore, our stance today is that our students can blow the whistle on industry, either internally or externally. But he can do it by being a productive management team, even when we're not so designated. Our responsibility as educators is to set them up, to make them aware that this

is their responsibility. We find it very difficult to preach morals or to teach a definite set of ethics. But we feel that each person should be encouraged to express the set of ethics that he personally has developed. We do hope that our engineers can go out and be actualized people, be non-manipulative, be open. They can express their concern about what the company is doing, about its processes, about the pollution capability, about the discrimination practices that they see, about the quality or lack of quality of their product. These are of direct concern to every technical person who works with a company, and the first step, the most productive step, is one of immediately being interactive.

**"Had I but served my God with the zeal  
that I have served my king, He would not,  
in my old age, have left me naked before  
my enemies!"—William Shakespeare**

## **ChE** book reviews

### **Modeling Crystal Growth Rate from Solution**

*By Makoto Ohara and Robert C. Reid  
Prentice-Hall (1973), 272 pp.*

Reviewed by Maurice Larson, Iowa State U.

This book is a good summary of the most popular theories attempting to describe the mechanism of crystal growth from solution. Of its 272 pages, 134 pages are devoted to appendices. It is printed by photo-offset of the typed manuscript. It is well organized and readable, but many of the illustrations do not have figure numbers nor titles. This leads to some difficulty. The index is adequate but brief.

The seven chapters of the non-appendix portion of the book are devoted to a Synopsis of the text, four chapters describing four growth mechanism concepts, one chapter concerned with impurity effects and a chapter which compares recent experimental data with theory.

The Synopsis summarizes the book well, points out what the purpose of the book is and briefly states the concepts of the various mechanistic models for growth. Chapter 2 discusses the classical surface nucleation theories of growth and shows that they are perhaps quite inadequate to explain observed growth rates. Chapter 3 discusses crystal growth limited by mass transfer,

introduces the Burton, Caberra, Frank bulk diffusion model and treats it in detail. Chapter 4 discusses surface diffusion theories, again calling on the work of Burton, Caberra and Frank. The chapter is quite short leaving the detailed mathematical development for Appendix A which is 68 pages long. The treatment is detailed and lucid. Layer and dislocation growth concepts are adequately treated.

Chapter 5 attempts to account for the appearance of microscopic growth layers and distinguishes them from the layer and dislocation growth theories of Burton, Caberra and Frank. Impurity effects are briefly treated in chapter 6. The treatment reflects the general lack of adequate theories which explain observed phenomena. Finally chapter 7 presents data which can be explained to some degree by the theories presented previously.

The book is largely concerned with the detailed mathematical presentation of existing theories and the correction of some derivation errors found in the literature. In the words of the authors 'the book has solved no *new* (italics mine) problem' but the treatment should be helpful for those wishing to gain an understanding of present thought without extensive literature review. It will be a good reference book for those new to the field and could provide a substantial part of text material for a course in crystallization technology.

## DIGITAL COMPUTATIONS: Liu

Continued from page 169.

propositions. What is perhaps the most encouraging of all is the interest in this course and the constructive criticism by the class.

### ACKNOWLEDGMENT

The research grants provided by the Alabama's Water Resources Research Institute and the Auburn University Grant-in-Aid Program on projects concerning the course subject are gratefully acknowledged. □

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## MEASURES OF EXCELLENCE: Bernier, Gill and Hunt

Continued from page 197.

- '67-9 and cited ten or more times.
10. Papers/professor: Works published in the '67-9 period divided by the number of professors, publishing or not, in the departments in that period.
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  13. 1970 Rating of Graduate Programs: Detailed data of Roose and Andersen study on rankings of departments of ChE kindly supplied by Andersen.
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## CPM METHOD: Donaghey

Continued from page 193.

The acceleration of any project step presupposes a subcontracting of project labor, often at the expense of graduate research experience. For example, the time required for construction of experimental apparatus can be shorted by purchasing ready-made apparatus, and data-reduction tasks could possibly be shortened by hiring an undergraduate assistant.

With accelerated project rates now accepted for tasks 4, 6 and 7, the resulting critical path becomes that shown in Fig. 1c. Here, the total project time is constrained by the duration of task 2 (i.e., waiting for ordered supplies to arrive) rather than by steps 6 and 4. Consequently, one of the two tasks need not be shortened.

TABLE III. Precedence-Contribution Matrix

Tasks Affected	1	2	3	4	5	6	7	8	9
1		P	C	P		P			P
2					P				
3									
4		C			P				
5	C	C		C			P		
6	C		C					P	
7			C			C		P	
8						C			P
9			C		C	C	C	C	

P = Precedence      C = Contribution

Table I shows that task 6 has the higher cost slope, and, therefore, this task should be carried out at the normal rate.

### RECENT RESULTS

THE CRITICAL PATH method outlined above has been tested in a number of graduate research programs in solid-state electrochemistry, process kinetics and transport phenomena during the past few years. Experience has shown that the initial critical path plan must be revised periodically during the program to take advantages of new discoveries or to avoid limiting difficulties. Experience has also shown a high correlation between task identification and effective task completion by the student. It has also been found that long-term segments of the total program should be subdivided so that the student gains familiarity with all type of program tasks in operation terms early in the program.

TABLE IV. Assignment of Topical Sequences

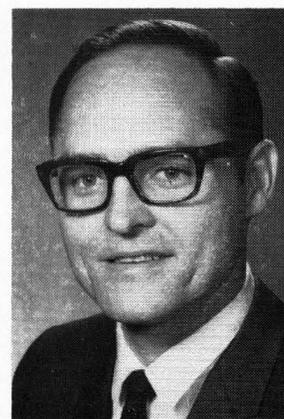
Sequence	Step Number					
	1	2	3	4	5	6
A	1	2	5	7	8	9
B	3					
C		4	5	7	8	9
D		6				

### CONCLUSIONS

THE FORM OF THE critical path method presented here differs from earlier forms in having these important characteristics: (1) the educational experience derived from interacting research tasks is counted as a cost benefit, (2) the critical path is constructed with a minimum of subcontracted or simultaneous tasks, and (3) the method presented does not require a computer to apply it. □

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Lee F. Donaghey received the B.A. degree in Physics from Harvard College, and the M.S. and Ph.D. degrees in Materials Science from Stanford University. His industrial experience has been in the semiconductor and microwave electronics industries. Following a postdoctoral appointment at the Royal Institute of Technology, Stockholm, he joined the Chemical Engineering faculty at the University of California, Berkeley in 1970. His research interests are concerned with the synthesis, thermochemistry and process kinetics of electronic materials.

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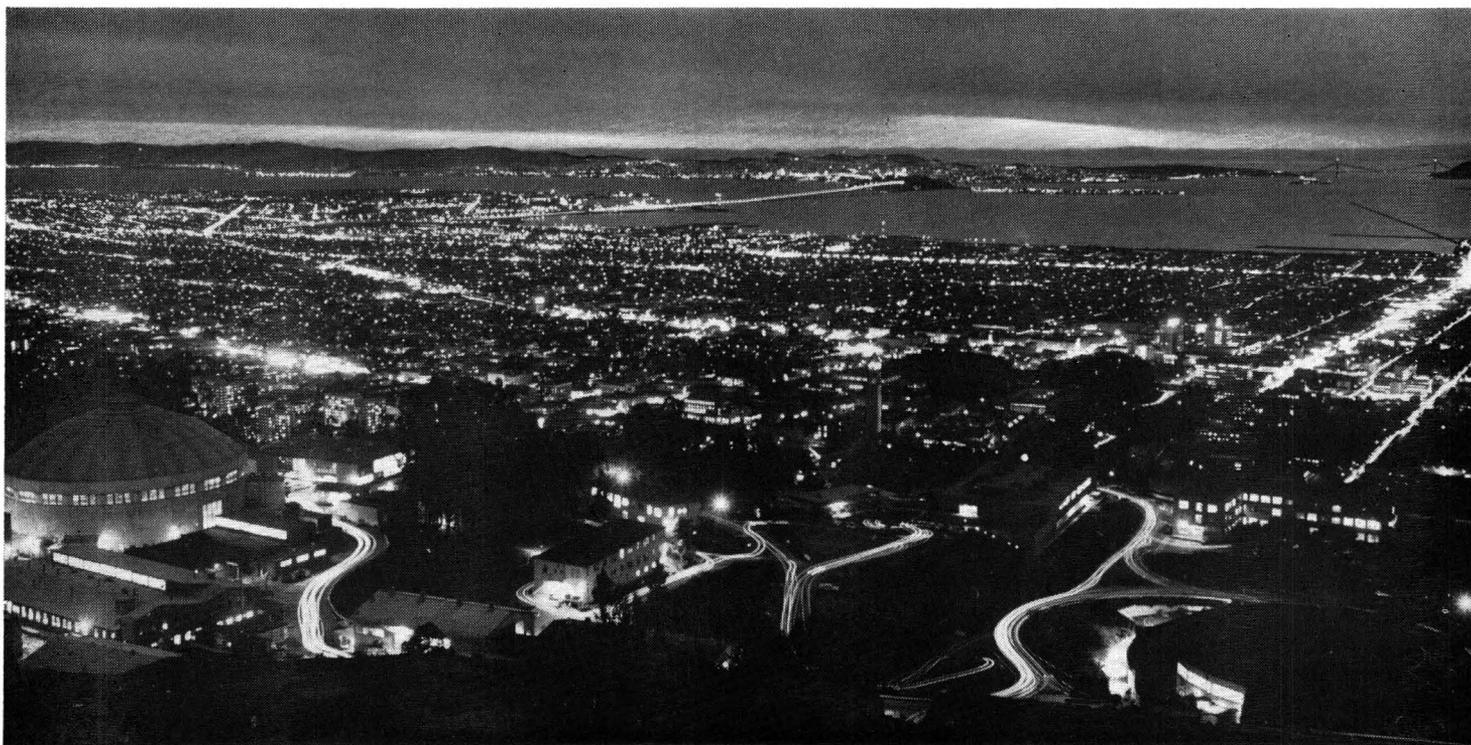
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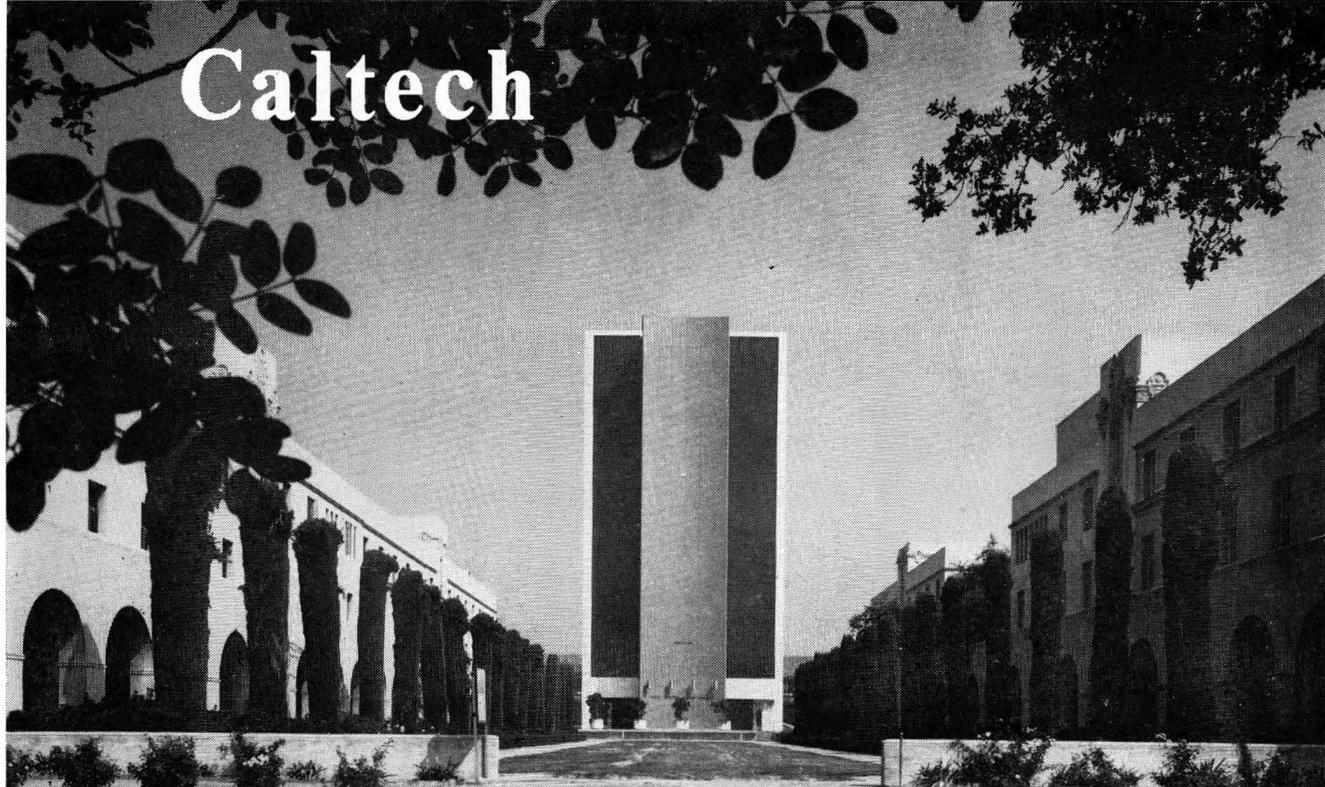
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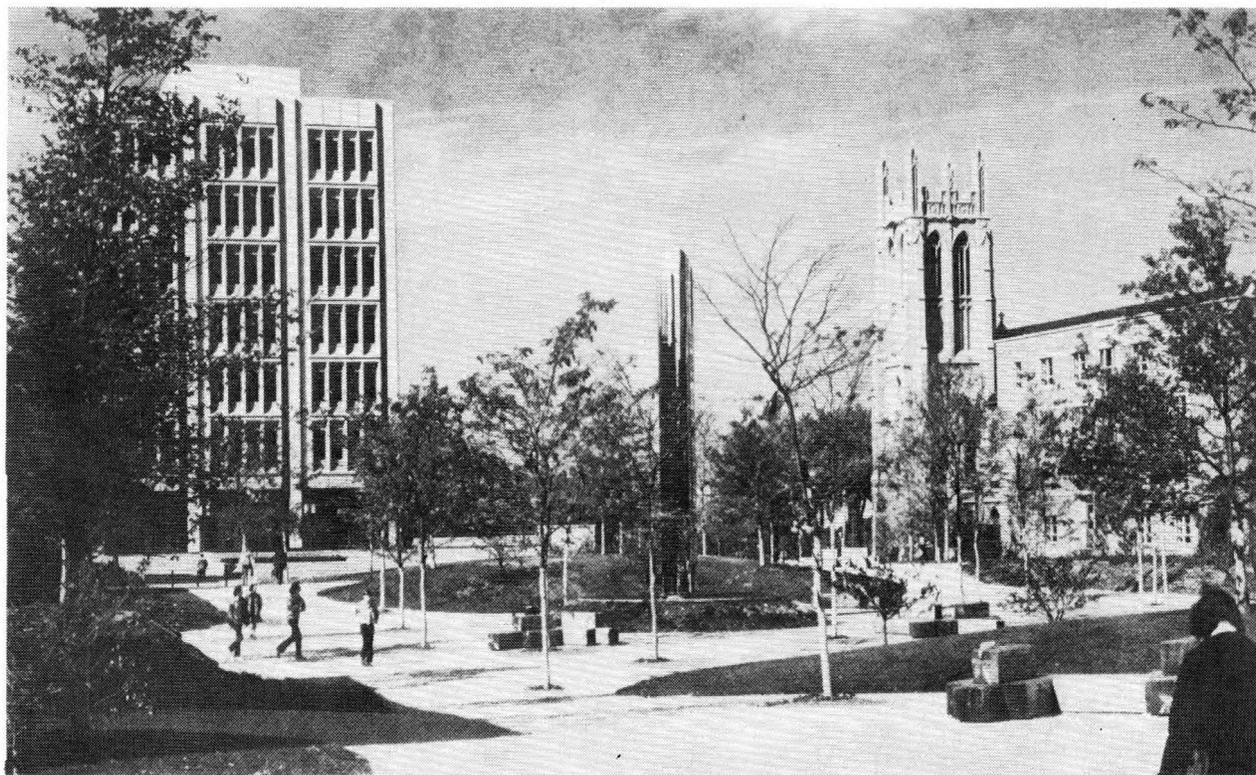
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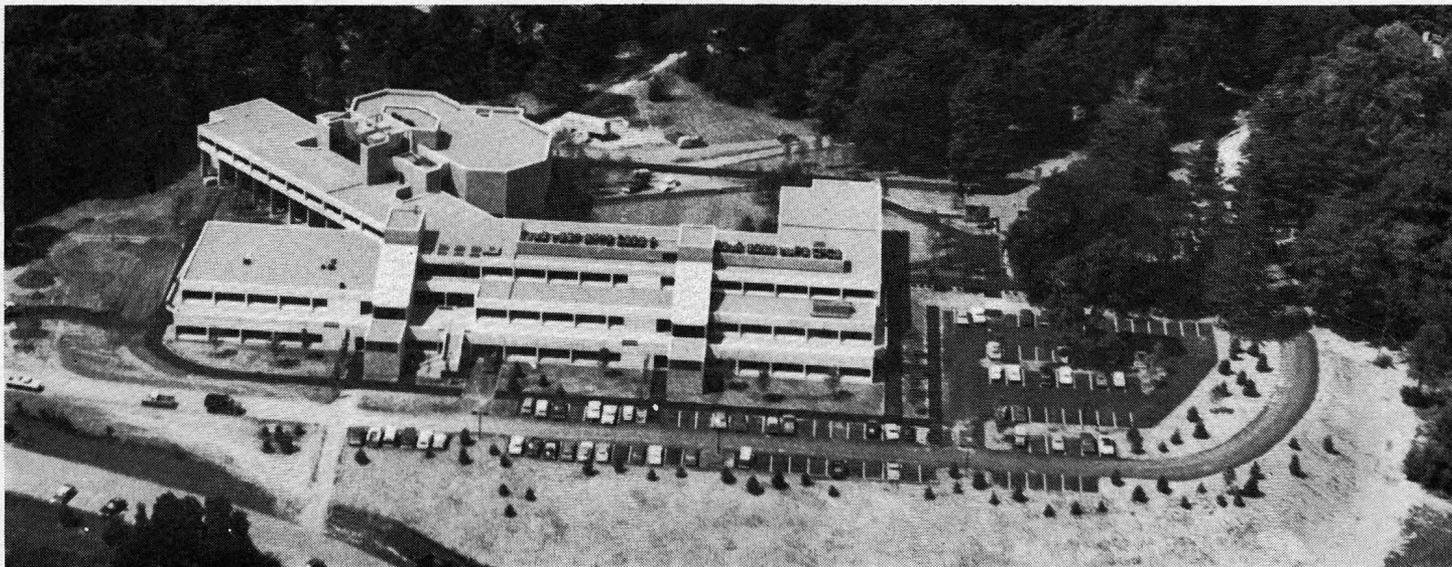
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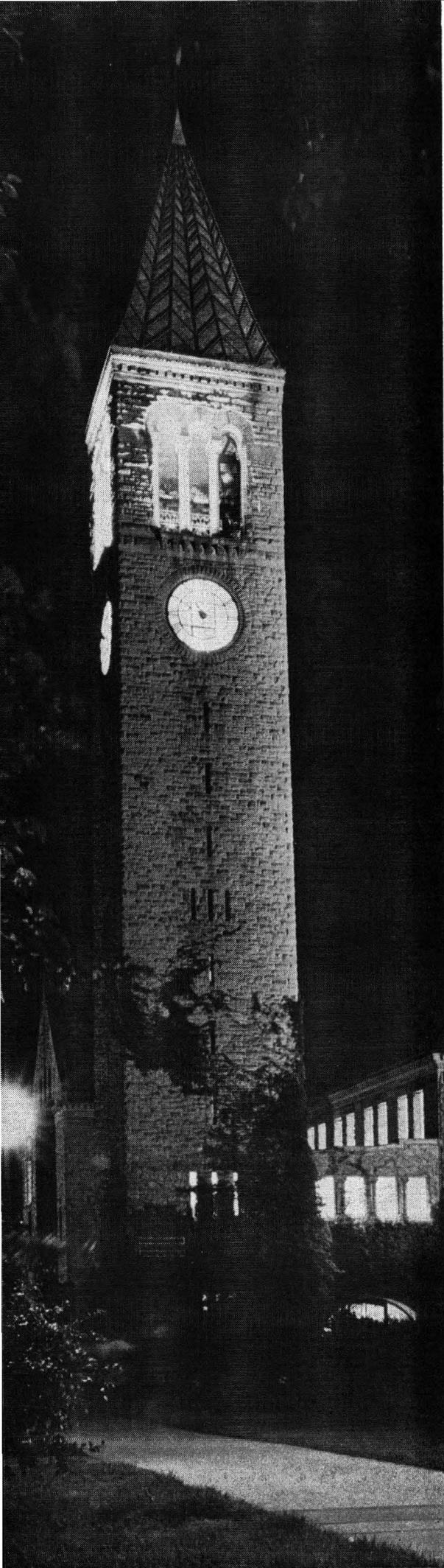
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B. C. Gates	S. I. Sandler
D. H. Henneman, M.D.	G. C. A. Schuit (½ time)
J. R. Katzer	J. M. Schultz
R. L. McCullough	L. Spielman
A. B. Metzner	James Wei

The adjunct and research faculty who provide extensive association with industrial practice are:

L. A. DeFrate	Heat, mass and momentum transfer
T. R. Keane	Polymer Science & Engineering
W. H. Manogue	Catalysis, reaction engineering
E. L. Mongan, Jr.	Design and process evaluation
F. E. Rush, Jr.	Mass transfer—distillation, absorption, extraction
R. J. Samuels	Polymer science
A. B. Stiles	Catalysis
K. F. Wissbrun	Polymer engineering

For information and admissions materials contact:

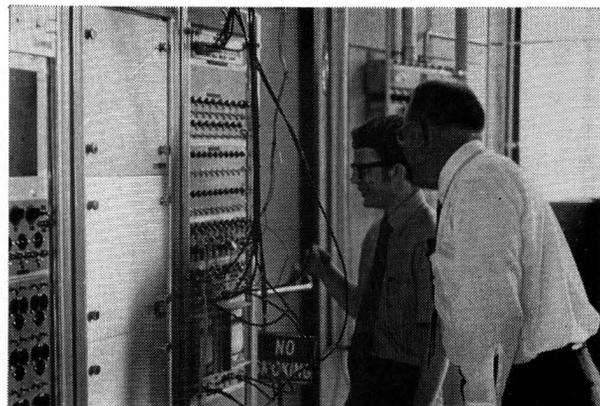
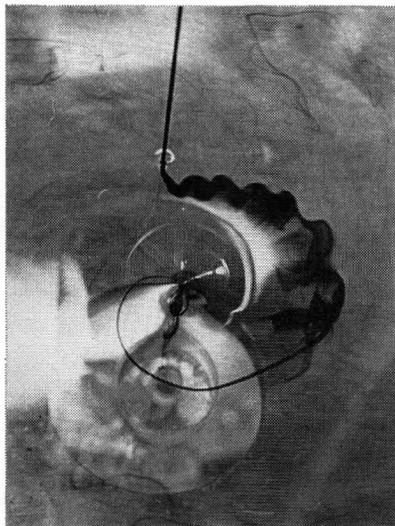
A. B. Metzner, Chairman

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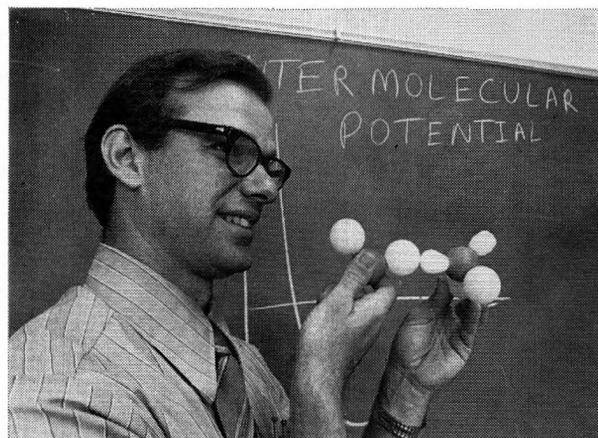
## *Transport Phenomena & Rheology*

Drag-reducing polymers greatly modify the familiar bathtub vortex, as studied here by dye injection.



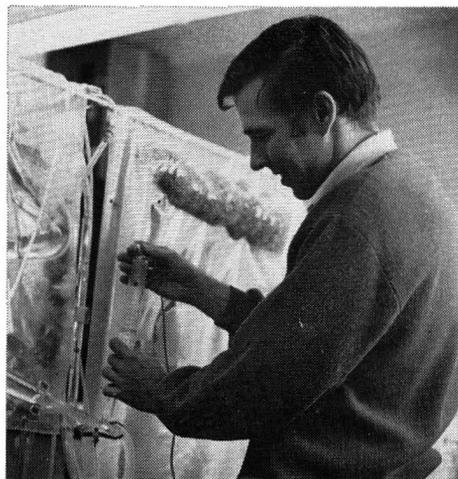
## *Optimization & Control*

Part of a computerized distillation control system.



## *Thermodynamics & Statistical Mechanics*

Illustrating hydrogen-bonding forces between water molecules.



## *Biomedical Engineering & Interfacial Phenomena*

Oxygen being extracted from a substance similar to blood plasma.

*and much more...*

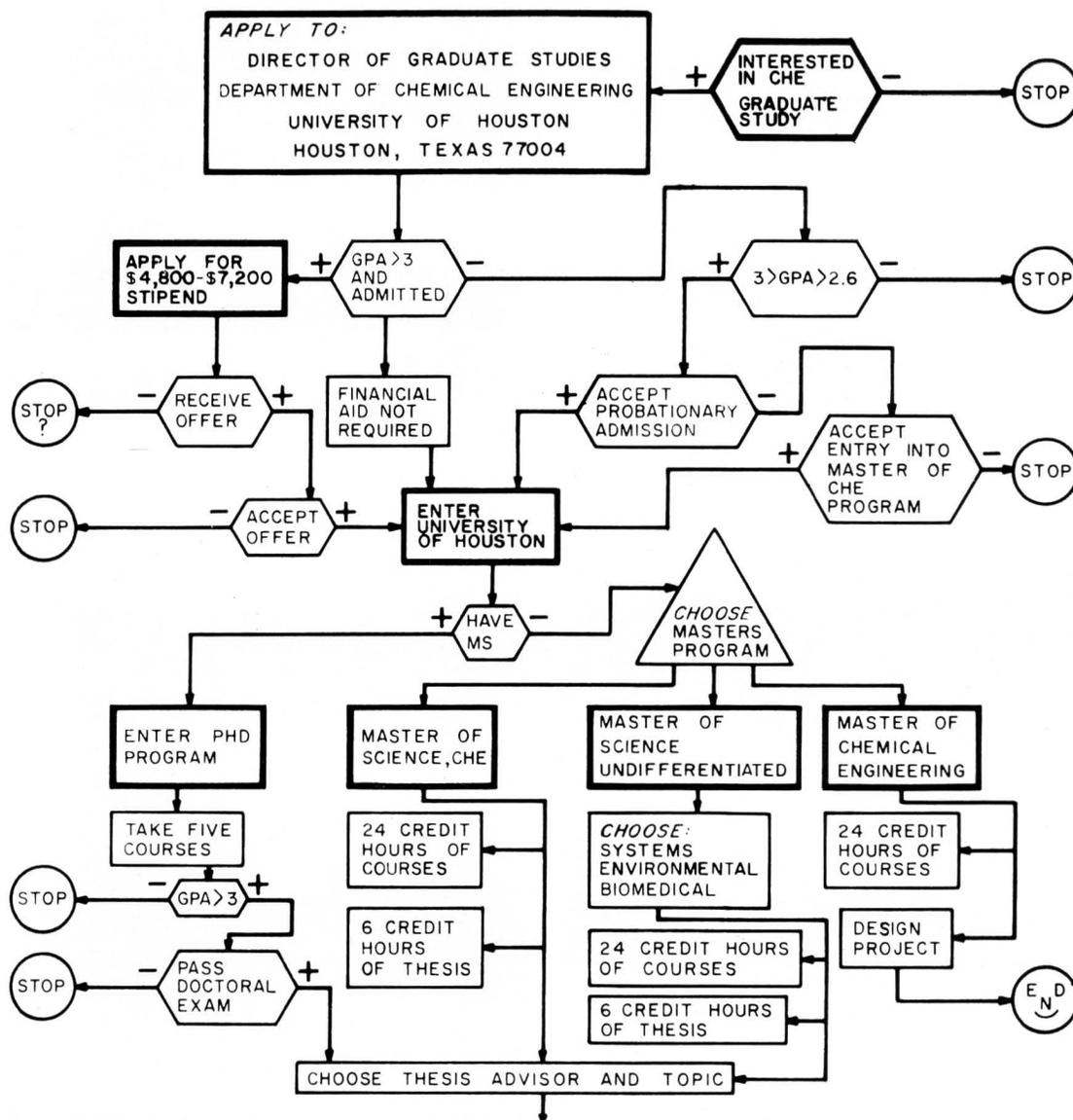
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*Write to:*

*Dr. John C. Biery, Chairman  
Department of Chemical Engineering - Room 227  
University of Florida  
Gainesville, Florida 32611*

Chemical Engineering  
Graduate Study Programs

**UNIVERSITY OF HOUSTON**



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J.R. CRUMP	W.I. HONEYWELL	R.L. MOTARD	F.M. TILLER
A.E. DUKLER	C.J. HUANG	A.C. PAYATAKES	C.F. WALTER
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 KINETICS ... ENERGY CONVERSION ... ENZYME KINETICS ... HEAT AND  
 MASS TRANSFER ... THERMODYNAMICS ... AIR POLLUTION ... COMPUTER  
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 BIOMEDICAL SYSTEMS ... RHEOLOGY ... FLUID - PARTICLE  
 SEPARATIONS ... PROCESS SYNTHESIS ... REACTOR DESIGN ...

END

# ILLINOIS

## THE DEPARTMENT OF CHEMICAL ENGINEERING UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

- **GOALS OF GRADUATE STUDY:** This Department offers M.S. and Ph.D. programs with a strong emphasis on creative research, either in fundamental engineering science or its application to the solution of current problems of social concern. Truly exceptional educational experiences may be achieved from the close one-to-one interaction of a student with a professor as together they develop relevant scientific contributions.
- **STAFF AND FACILITIES:** The faculty of the Department are all highly active in both teaching and research; they have won numerous national and international awards for their achievements. Moreover, outstanding support for graduate research is available, not only in terms of equipment and physical facilities but also from the many shops, technicians, and service personnel.
- **AREAS OF RESEARCH:** Applied Mathematics  
Biological Applications of Chemical Engineering  
Chemical Kinetics  
Chemical Reactor Dynamics  
Corrosion  
Electronic Structure of Matter  
Electrochemical Engineering  
Energy Sources and Conservation  
Environmental Engineering  
Fluid Dynamics  
Heat Transfer  
High Pressure  
Mass Transfer  
Materials Science and Engineering  
Molecular Thermodynamics  
Phase Transformations  
Process Control  
Reaction Engineering  
Statistical Mechanics  
Two-Phase Flow
- **FOR INFORMATION AND APPLICATIONS:** Professor J. W. Westwater  
Department of Chemical Engineering  
113 Adams Laboratory  
University of Illinois  
Urbana, Illinois 61801

# IOWA STATE UNIVERSITY

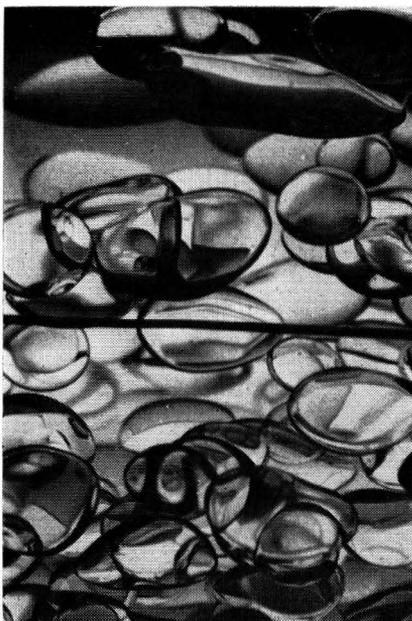
## OF SCIENCE AND TECHNOLOGY



### Energy Conversion (Coal Tech, Hydrogen Production, Atomic Energy)

Dr. R. G. Bautista  
Dr. L. E. Burkhart  
Dr. G. Burnet  
Dr. A. H. Pulsifer  
Dr. D. L. Ulrichson  
Dr. T. D. Wheelock

### GRADUATE STUDY and GRADUATE RESEARCH in Chemical Engineering



### Transport Processes (Heat, mass & momentum transfer)

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Dr. R. G. Bautista  
Dr. C. E. Glatz  
Dr. J. C. Hill  
Dr. F. O. Shuck

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Dr. G. Burnet  
Dr. M. A. Larson

### Biomedical Engineering

(System Modeling,  
Transport, process)  
Dr. R. C. Seagrave

### Biochemical Engineering

(Enzyme Technology)  
Dr. C. E. Glatz  
Dr. P. J. Reilly

### Polymerization Processes

Dr. W. H. Abraham  
Dr. J. D. Stevens

as well as

Air Pollution Control  
Solvent Extraction  
High Pressure Technology  
Mineral Processing

### Crystallization Kinetics

Dr. M. A. Larson  
Dr. J. D. Stevens

### Process Instrumentation and System Optimization and Control

Dr. L. E. Burkhart  
Dr. K. R. Jolls

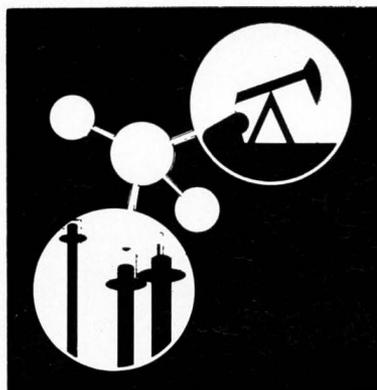
write to:

Prof. M. A. Larson  
Dept. of Chem. Engr. & Nuc. Engr.  
Iowa State University  
Ames, Iowa 50010



# **UNIVERSITY OF KANSAS**

Department of Chemical and Petroleum Engineering



M.S. and Ph.D. Programs  
in  
Chemical Engineering  
M.S. Program  
in  
Petroleum Engineering  
also  
Doctor of Engineering (D.E.)  
and  
M.S. in Petroleum Management

The Department is the recent recipient of a large state grant for research in the area of Tertiary Oil Recovery to assist the Petroleum Industry.

Financial assistance is  
available for Research Assistants  
and Teaching Assistants

## **Research Areas**

**Transport Phenomena**

**Fluid Flow in Porous Media**

**Process Dynamics and Control  
Water Resources and  
Environmental Studies**

**Mathematical Modeling of  
Complex Physical Systems**

**Reaction Kinetics and  
Process Design**

**Nucleate Boiling**

**High Pressure, Low Temperature  
Phase Behavior**

**For Information and Applications write:**

Floyd W. Preston, Chairman  
Dept. of Chemical and Petroleum Engineering  
University of Kansas  
Lawrence, Kansas, 66044  
Phone (913) UN4-3922

UNIVERSITY OF KENTUCKY

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M.S. & Ph.D. Programs  
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## ENERGY ENGINEERING

Energy supply and demand  
Fuel combustion processes  
Coal liquefaction and gasification processes

## AIR POLLUTION CONTROL

Rates and equilibria of atmospheric reactions  
Process and system control, and gas cleaning  
Diffusion, and modelling of urban atmospheres

## WATER POLLUTION CONTROL

Advanced waste treatment and water reclamation  
Design of physical and chemical processes  
Biochemical reactor design

## STIPENDS:

Excellent financial support is available  
in the form of National Science Foundation  
Traineeships, fellowships & assistantships.

## OTHER PROGRAM AREAS:

Thermodynamics  
Process control

Reactor design  
Transport



**WRITE TO:** R.B. Grieves, Chairman  
Dept. of Chemical Engineering  
UNIVERSITY OF KENTUCKY  
LEXINGTON, KENTUCKY 40506



Massachusetts  
Institute  
of Technology

DEPARTMENT OF  
CHEMICAL ENGINEERING

- ENVIRONMENTAL QUALITY
- BIOCHEMICAL ENGINEERING
- BIOMEDICAL ENGINEERING
- TRANSPORT PHENOMENA
- CHEMICAL ENGINEERING SYSTEMS
- SURFACE CHEMISTRY AND TECHNOLOGY
- POLYMERS AND MACROMOLECULES
- ENERGY

For decades to come, the chemical engineer will play a central role in fields of national concern. In two areas alone, energy and the environment, society and industry will turn to the chemical engineer for technology and management in finding process related solutions to critical problems. M.I.T. has consistently been a leader in chemical engineering education with a strong working relationship with industry for over a half century. For detailed information, contact Professor Raymond F. Baddour, Head of the Department of Chemical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139.

FACULTY

Raymond F. Baddour  
Lawrence B. Evans  
Paul J. Flory  
Hoyt C. Hottel  
John P. Longwell  
James E. Mark  
Herman P. Meissner  
Edward W. Merrill  
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J. R. A. Pearson

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Clark K. Colton  
Jack B. Howard  
Michael Modell

C. Michael Mohr  
James H. Porter  
Robert C. Armstrong  
Donald B. Anthony  
Lloyd A. Clomburg  
Robert E. Cohen  
Richard G. Donnelly  
Christos Georgakis  
Ronald A. Hites  
Jefferson W. Tester

Department of Chemical Engineering

# UNIVERSITY OF MISSOURI — ROLLA

ROLLA, MISSOURI 65401

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Contact Dr. M. R. Strunk, Chairman

Day Programs                      M.S. and Ph.D. Degrees

---

Established fields of specialization in which research programs are in progress are:

- (1) Fluid Turbulence and Drag Reduction Studies  
—Drs. J. L. Zakin and G. K. Patterson
- (2) Electrochemistry and Fuel Cells—Dr. J. W. Johnson
- (3) Heat Transfer (Cryogenics) Dr. E. L. Park, Jr.
- (4) Mass Transfer Studies—Dr. R. M. Wellek
- (5) Structure and Properties of Polymers—Dr. K. G. Mayhan

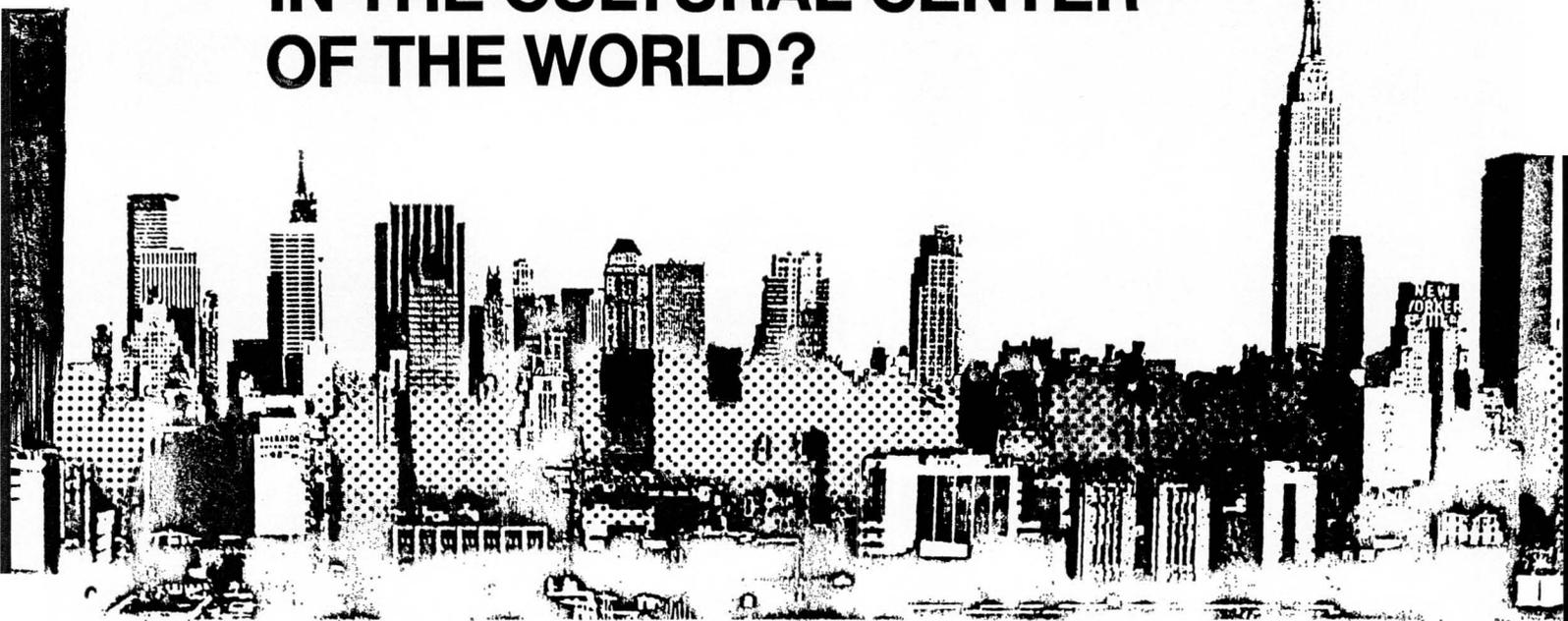
In addition, research projects are being carried out in the following areas:

- (a) Optimization of Chemical Systems; Energy Conversion from Agricultural Products—Prof. J. L. Gaddy
- (b) Design Techniques and Fermentation Studies—Dr. M. E. Findley
- (c) Multi-component Distillation Efficiencies—Dr. R. C. Waggoner
- (d) Gas Permeability Studies—Dr. R. A. Primrose
- (e) Separations by Electrodialysis Techniques—Dr. H. H. Grice
- (f) Process Dynamics and Control; Computer Applications to Process Control—Drs. M. E. Findley, R. C. Waggoner, and R. A. Mollenkamp
- (g) Transport Properties, Kinetics and enzymes and catalysis—Dr. O. K. Crosser and Dr. B. E. Poling
- (h) Thermodynamics, Vapor-Liquid Equilibrium—Dr. D. B. Manley



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

# HOW WOULD YOU LIKE TO DO YOUR GRADUATE WORK IN THE CULTURAL CENTER OF THE WORLD?



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## **RESEARCH AREAS**

Air Pollution  
Biomedical Systems  
Catalysis, Kinetics and Reactors  
Fluidization  
Fluid Mechanics  
Heat and Mass Transfer  
Mathematical Modelling  
Polymerization Reactions  
Process Control  
Rheology and Polymer Processing

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Programs leading to Master's, Engineer and  
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engineering, bioengineering and environmental  
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## **For further information contact**

Professor C. D. Han  
Head, Department of Chemical Engineering  
Polytechnic Institute of New York  
333 Jay Street  
Brooklyn, New York 11201



## PHILADELPHIA

The cultural advantages and historical assets of a great city, including the incomparable Philadelphia Orchestra are within walking distance of the University. Enthusiasts will find a variety

of college and professional sports at hand. A complete range of recreational facilities exists within the city. The Pocono Mountains and the New Jersey shore are within a two hour drive.

## UNIVERSITY OF PENNSYLVANIA

The University of Pennsylvania is an Ivy League School emphasizing scholarly activity and excellence in graduate education. A unique feature of the University is the breadth of medically related activities including those in engineering. In recent years the University has undergone

a great expansion of its facilities, including specialized graduate student housing. The Department of Chemical and Biochemical Engineering has attracted national and international attention because of its rapid rise to excellence.

## DEPARTMENT OF CHEMICAL AND BIOCHEMICAL ENGINEERING

The faculty includes two members of the National Academy of Engineering and three recipients of the highest honors awarded by the American Institute of Chemical Engineers. Every staff member is active in graduate and under-

graduate teaching, in research, and in professional work. Close faculty association with industry provides expert guidance for the student in research and career planning.

### FACULTY

Stuart W. Churchill (Michigan)  
Elizabeth Dussan V. (Johns Hopkins)  
William C. Forsman (Pennsylvania)  
David J. Graves (M.I.T.)  
A. Norman Hixson (Columbia)  
Arthur E. Humphrey (Columbia)  
Ronald L. Klaus (R.P.I.)

Mitchell Litt (Columbia)  
Alan L. Myers (California)  
Melvin C. Molstad (Yale)  
Leonard Nanis (Columbia)  
Daniel D. Perlmutter (Yale)  
John A. Quinn (Princeton)  
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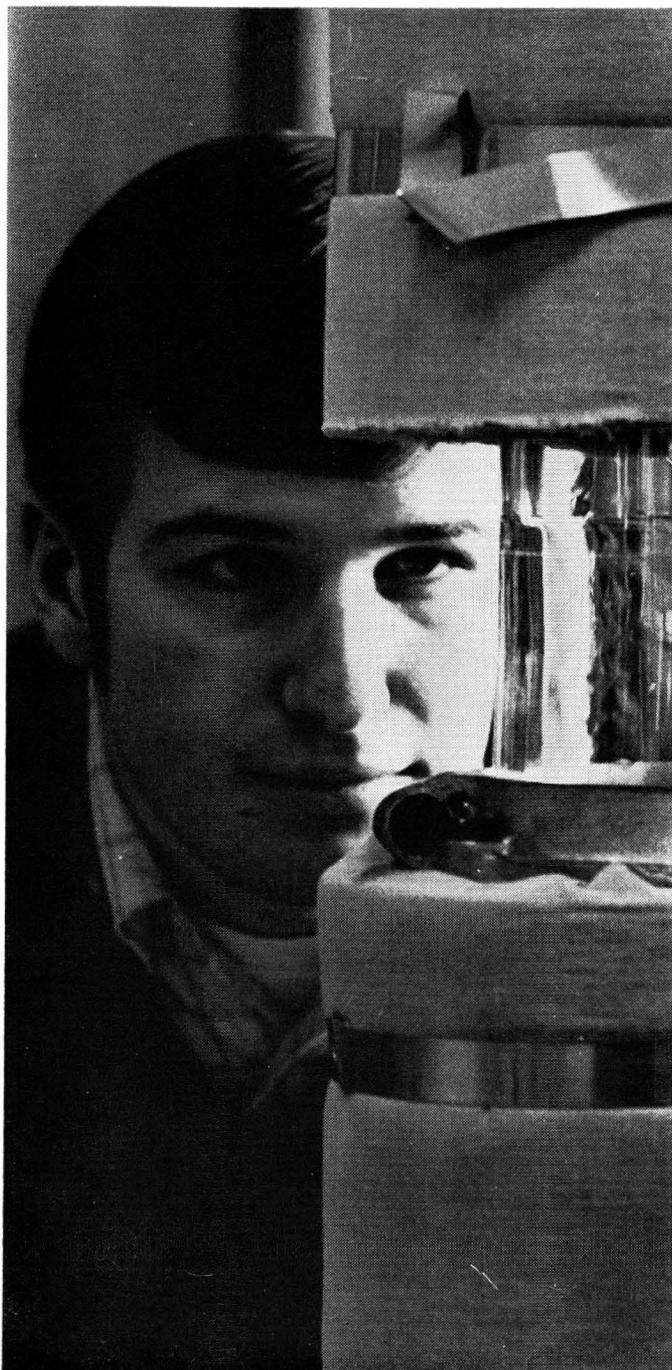
### RESEARCH SPECIALTIES

Energy Utilization and Conservation  
Enzyme Engineering  
Biomedical Engineering  
Computer-Aided Design  
Chemical Reactor Analysis  
Electrochemical Engineering

Environmental and Pollution Control  
Polymer Engineering  
Process Simulation  
Surface Phenomena  
Separations Techniques  
Biochemical Engineering

**For further information on graduate studies in this dynamic setting, write to:  
Dr. J. A. Quinn, Department of Chemical and Biochemical Engineering,  
University of Pennsylvania, Philadelphia, Pa. 19174.**

# LOOKING



for a  
graduate education  
in  
Chemical Engineering ?

Consider

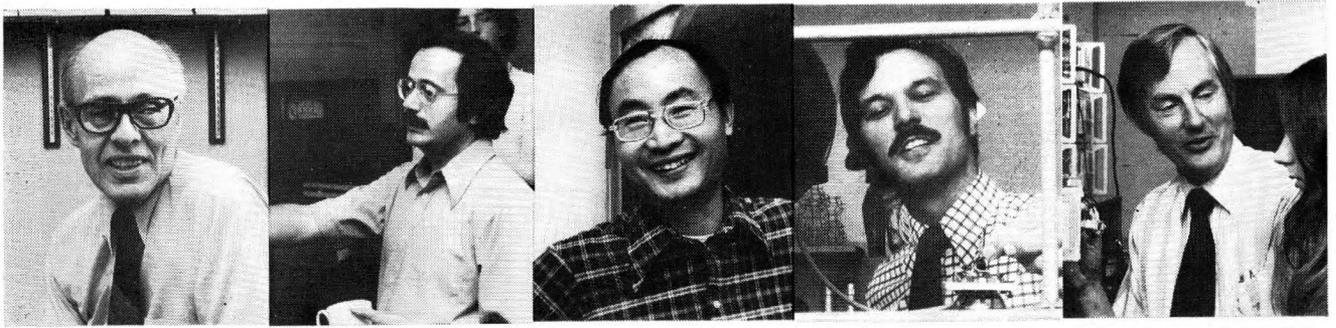
## **PENN STATE**

**M.S. and Ph.D. Programs Offered  
with Research In**

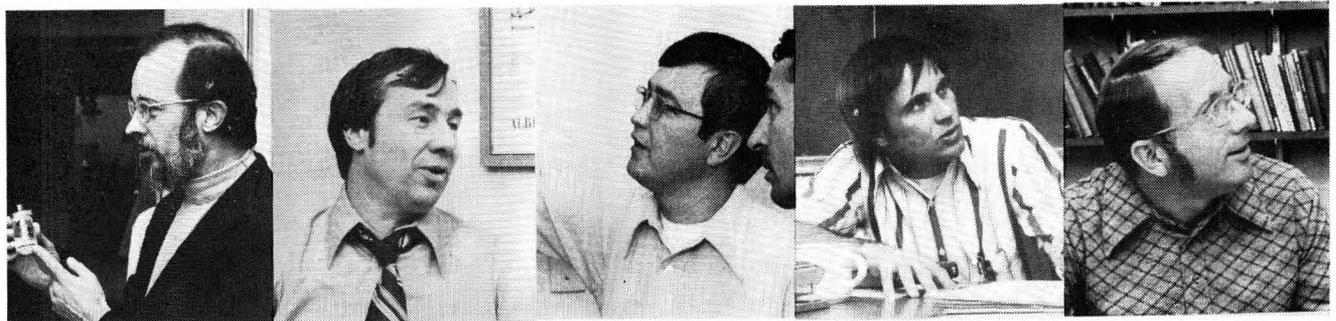
Biomedical Engineering  
Environmental Research  
Reactor Design and Catalysis  
Transport Phenomena  
Thermodynamic Properties  
Separational Processes  
Applied Chemistry and Kinetics  
Petroleum Refining  
Tribology  
Interfacial Phenomena  
Energy Research  
And Other Areas

WRITE TO

Prof. Lee C. Eagleton, Head  
160 Fenske Laboratory  
The Pennsylvania State University  
University Park, Pa. 16802

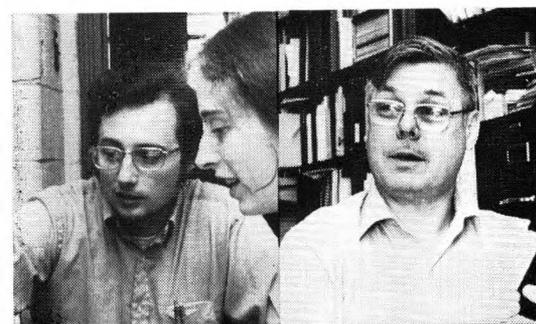
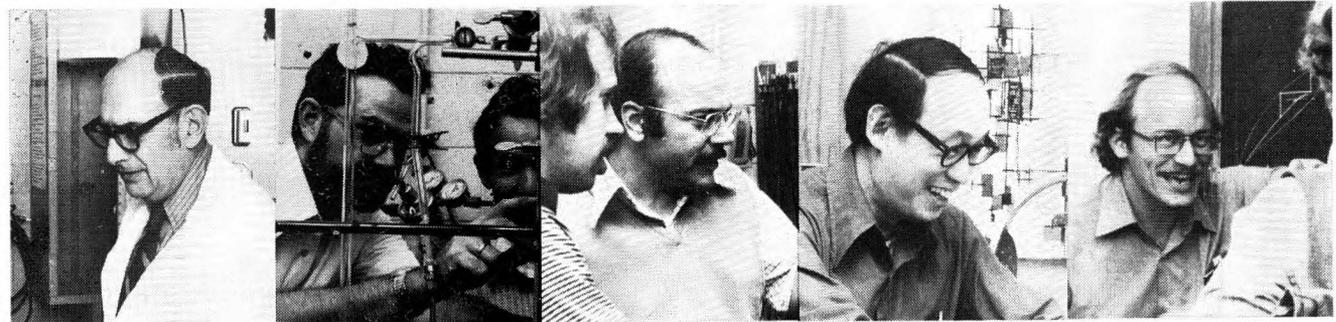
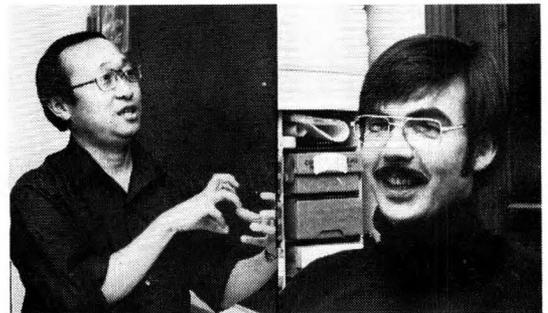


# PURDUE



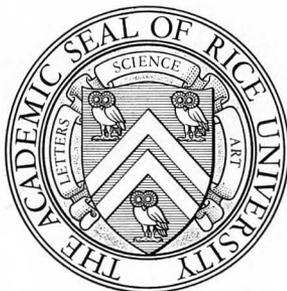
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Chemical Engineering  
Purdue University  
West Lafayette, Indiana 47907





# Graduate Study in Chemical Engineering at Rice University

Graduate study in Chemical Engineering at Rice University is offered to qualified students with backgrounds in the fundamental principles of Chemistry, Mathematics, and Physics. The curriculum is aimed at strengthening the student's understanding of these principles and provides a basis for developing in certain areas the necessary proficiency for conducting independent research. A large number of research programs are pursued in various areas of Chemical Engineering and related fields, such as Biomedical Engineering and Polymer Science. A joint program with the Baylor College of Medicine, leading to M.D.-Ph.D. and M.D.-M.S. degrees is also available.

The Department has approximately 35 graduate students, predominantly Ph.D. candidates. There are also several post-doctoral fellows and research engineers associated with the various laboratories. Permanent faculty numbers 12, all active in undergraduate and graduate teaching, as well as in research. The high faculty-to-student ratio, outstanding laboratory facilities, and stimulating research projects provide a graduate education environment in keeping with Rice's reputation for academic excellence. The Department is one of the top 15 Chemical Engineering Departments in the U.S., ranked by graduate faculty quality and program effectiveness, according to a recent evaluation by the American Council of Education.

## MAJOR RESEARCH AREAS

Thermodynamics and Phase Equilibria  
Chemical Kinetics and Catalysis  
Chromatography  
Optimization, Stability, and Process Control  
Systems Analysis and Process Dynamics  
Rheology and Fluid Mechanics  
Polymer Science

## BIOMEDICAL ENGINEERING

Blood Flow and Blood Trauma  
Blood Pumping Systems  
Biomaterials

## Rice University

Rice is a privately endowed, nonsectarian, coeducational university. It occupies an architecturally attractive, tree-shaded campus of 300 acres, located in a fine residential area, 3 miles from the center of Houston. There are approximately 2200 undergraduate and 800 graduate students. The school offers the benefits of a complete university with programs in the various fields of science and the humanities, as well as in engineering. It has an excellent library with extensive holdings. The academic year is from September to May. As there are no summer classes, graduate students have nearly four months for research. The school offers excellent recreational and athletic facilities with a completely equipped gymnasium, and the southern climate makes outdoor sports, such as tennis, golf, and sailing year-round activities.

FALL 1975

## FINANCIAL SUPPORT

Full-time graduate students receive financial support with tuition remission and a tax-free fellowship of \$333-400 per month.

## APPLICATIONS AND INFORMATION

Address letters of inquiry to:

Chairman  
Department of Chemical Engineering  
Rice University  
Houston, Texas 77001

## Houston

With a population of nearly two million, Houston is the largest metropolitan, financial, and commercial center in the South and Southwest. It has achieved world-wide recognition through its vast and growing petrochemical complex, the pioneering medical and surgical activities at the Texas Medical Center, and the NASA Manned Spacecraft Center.

Houston is a cosmopolitan city with many cultural and recreational attractions. It has a well-known resident symphony orchestra, an opera, and a ballet company, which perform regularly in the newly constructed Jesse H. Jones Hall. Just east of the Rice campus is Hermann Park with its free zoo, golf course, Planetarium, and Museum of Natural Science. The air-conditioned Astro-dome is the home of the Houston Astros and Oilers and the site of many other events.

225



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**Dr. M. W. Davis, Jr., Chairman  
Chemical Engineering Program  
College of Engineering  
University of South Carolina  
Columbia, S.C. 29208**

## THE CHEMICAL ENGINEERING FACULTY

B. L. Baker, Professor, Ph.D., North Carolina State University, 1955 (Process design, environmental problems, ion transport)

M.W. Davis, Jr., Professor, Ph.D., University of California (Berkeley), 1951 (Kinetics and catalysis, chemical process analysis, solvent extraction, waste treatment)

J. H. Gibbons, Professor, Ph.D., University of Pittsburgh, 1961 (Heat transfer, fluid mechanics)

P. E. Kleinsmith, Assistant Professor, Ph.D., Carnegie-Mellon University, 1972 (Transport phenomena, statistical mechanics)

F. P. Pike, Professor, Ph.D., University of Minnesota, 1949 (Mass transfer in liquid-liquid systems, vapor-liquid equilibria)

J. M. Tarbell, Assistant Professor, Ph.D., University of Delaware, 1974 (Thermodynamics, process dynamics)

V. Van Brunt, Assistant Professor, Ph.D., University of Tennessee, 1974 (Mass Transfer, Computer Modeling)

# GRADUATE STUDY

IN

# CHEMICAL ENGINEERING

AT

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Stanford University offers programs of study and research leading to master of science and doctor of philosophy degrees in chemical engineering with a number of financially attractive fellowships and assistantships available to outstanding students pursuing either program.

For further information and application blanks, write to:

Admissions Chairman  
Department of Chemical Engineering  
Stanford University  
Stanford, California 94305.

Closing date for applications is Feb. 15, 1976.

## FACULTY:

**ANDREAS ACRIVOS, Ph.D.,** University of Minnesota, 1954. Field: Fluid Mechanics.

**MICHEL BOUDART, Ph.D.,** Princeton University, 1950. Field: Kinetics and Catalysis.

**GEORGE M. HOMSY, Ph.D.,** University of Illinois, 1969. Field: Fluid Mechanics and Stability.

**ROBERT J. MADIX, Ph.D.,** University of California at Berkeley, 1964. Field: Surface Reactivity.

**DAVID M. MASON, Ph.D.,** California Institute of Technology, 1949. Field: Applied Chemical Kinetics.

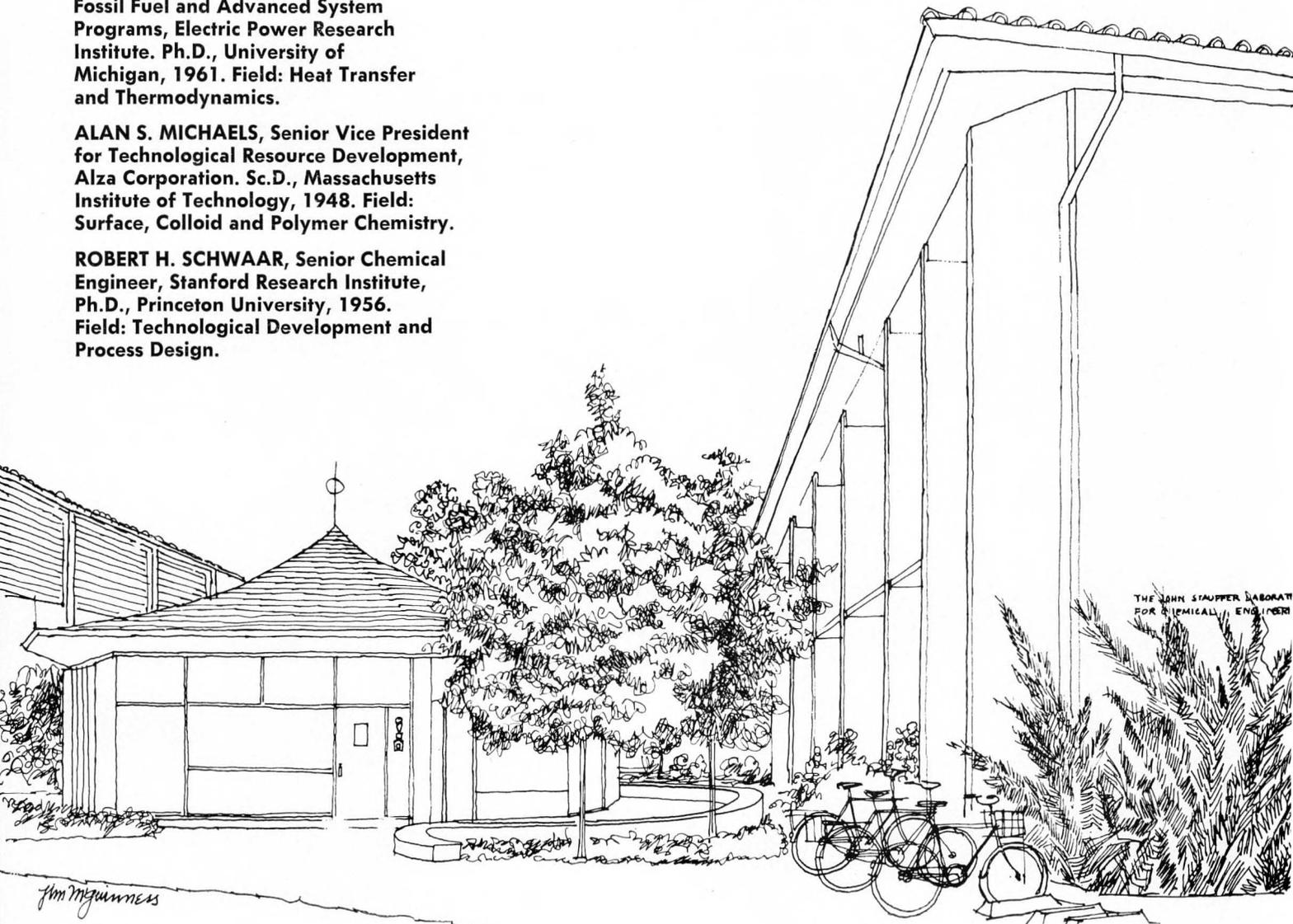
**CHANNING R. ROBERTSON, Ph.D.,** Stanford University, 1969. Field: Bioengineering.

## CONSULTING FACULTY:

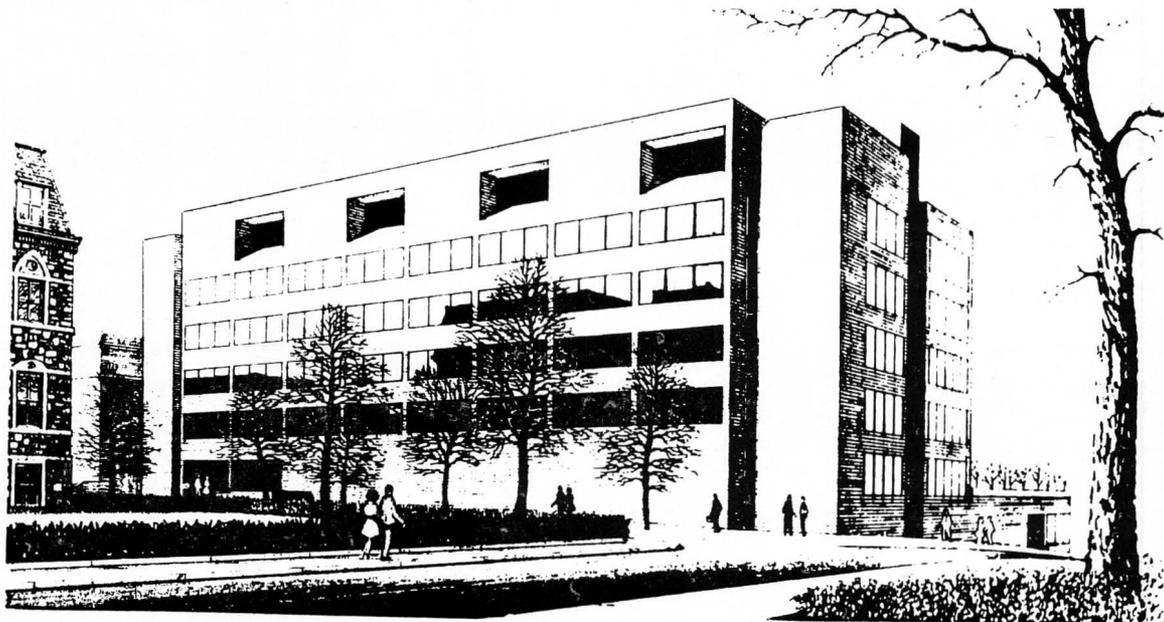
**RICHARD E. BALZHISER, Director of Fossil Fuel and Advanced System Programs, Electric Power Research Institute. Ph.D.,** University of Michigan, 1961. Field: Heat Transfer and Thermodynamics.

**ALAN S. MICHAELS, Senior Vice President for Technological Resource Development, Alza Corporation. Sc.D.,** Massachusetts Institute of Technology, 1948. Field: Surface, Colloid and Polymer Chemistry.

**ROBERT H. SCHWAAR, Senior Chemical Engineer, Stanford Research Institute, Ph.D.,** Princeton University, 1956. Field: Technological Development and Process Design.



*CHEMICAL ENGINEERING*  
*at*  
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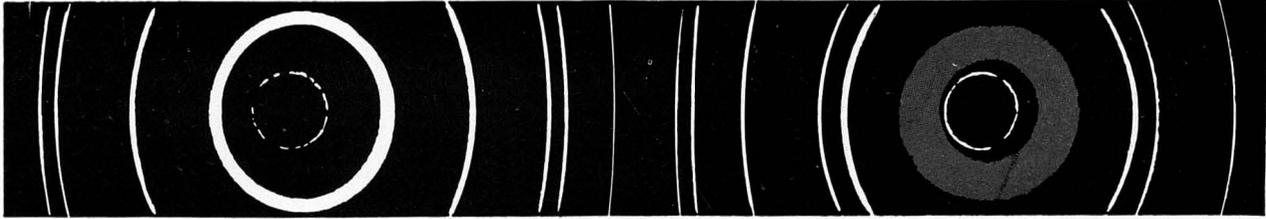


*MASTER'S and DOCTORATE PROGRAMS*  
*in*  
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*Design • Polymers*

*RESEARCH*  
*in*  
*Polymer Processing • Rheology*  
*Polymer Property-Structure Relationships*  
*Polymerization Kinetics • Reaction Engineering*  
*Mass Transfer • Fluid Dynamics • Turbulence*  
*Air Pollution • Waste Treatment • Combustion*  
*Energy Storage in Chemical Systems*

For further information contact:

Dean L. Z. Pollara  
Graduate Studies  
Stevens Institute of Technology  
Hoboken, New Jersey  
(201) 792-2700 Ext. 330



# THE UNIVERSITY OF TENNESSEE

---

## Programs

Programs for the degrees of Master of Science and Doctor of Philosophy are offered in both Chemical and Metallurgical Engineering. The Master's program may be tailored as a terminal one with emphasis on professional development, or it may serve as preparation for more advanced work leading to the Doctorate. Specialization in Polymer Science and Engineering is available at both levels.

---

## Faculty

William T. Becker  
Donald C. Bogue  
Charlie R. Brooks  
Edward S. Clark  
Oran L. Culberson  
John F. Fellers  
George C. Frazier  
Hsien-Wen Hsu  
Homer F. Johnson, Department Head  
Stanley H. Jury  
Carl D. Lundin  
Charles F. Moore  
Ben F. Oliver, Professor-in-Charge  
of Metallurgical Engineering  
Joseph J. Perona  
Joseph E. Spruiell  
E. Eugene Stansbury  
James L. White

FALL 1975

## Graduate Studies in Chemical & Metallurgical Engineering

---

## Research

Process Dynamics and Control  
Sorption Kinetics and Dynamics of  
Packed Beds  
Chromatographic and Ultracentrifuge  
Studies of Macromolecules  
Development and Synthesis of New  
Engineering Polymers  
Fiber and Plastics Processing  
Bioengineering  
X-Ray Diffraction, Transmission and  
Scanning Electron Microscopy  
Solidification, Zone Refining  
and Welding  
Cryogenic and High Temperature  
Calorimetry  
Flow and Fracture in Metallic and  
Polymeric Systems  
Corrosion  
Solid State Kinetics

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## Financial Assistance

Sources available include graduate teaching assistantships, research assistantships, and industrial fellowships.

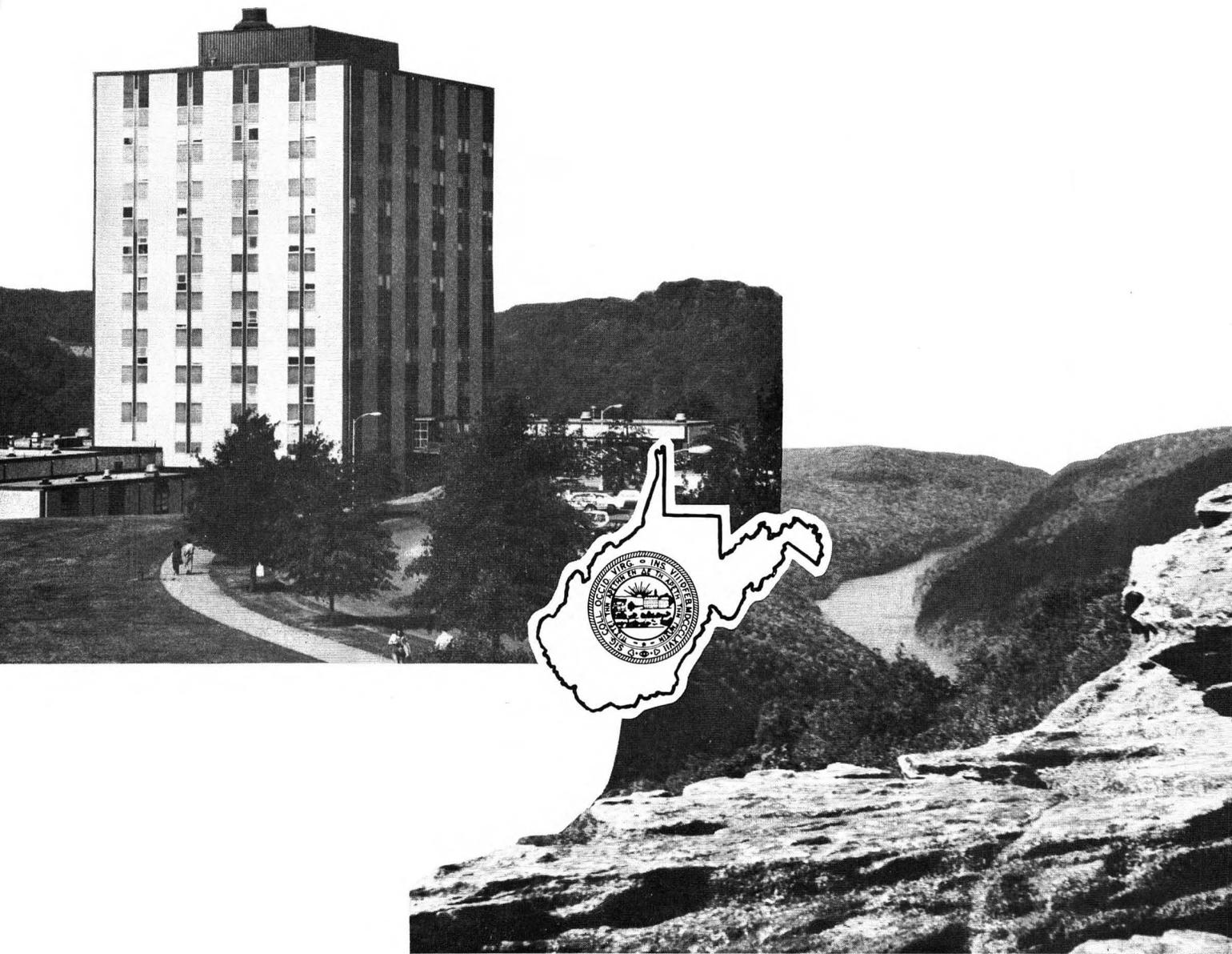
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## Knoxville and Surroundings

With a population near 200,000, Knoxville is the trade and industrial center of East Tennessee. In the Knoxville Auditorium-Coliseum and the University theaters, Broadway plays, musical and dramatic artists, and other entertainment events are regularly scheduled. Knoxville has a number of points of historical interest, a symphony orchestra, two art galleries, and a number of museums. Within an hour's drive are many TVA lakes and mountain streams for water sports, the Great Smoky Mountains National Park with the Gatlinburg tourist area, two state parks, and the atomic energy installations at Oak Ridge, including the Museum of Atomic Energy.

## Write

Chemical and Metallurgical Engineering  
The University of Tennessee  
Knoxville, Tennessee 37916



# West Virginia University Chemical Engineering

## Environmental Engineering

Purification of Acid Mine Drainage  
Water by Reverse Osmosis  
Sludge and Emulsion Dewatering  
SO<sub>2</sub> Scrubbing  
Economic Impact of Environmental  
Regulations

## Other Topics

Chemical Kinetics  
Separation Processes  
Optimization  
Transport Phenomena  
Utilization of Ultrasonic Energy  
Bioengineering  
Fluidization

## Energy Engineering

Coal Conversion  
Potential of Coal Based Energy Complexes  
Conversion of Solid Wastes to  
Low BTU Gas  
Energy Farming

## MS & PhD Programs

Financial Aid: up to \$5400/year  
For further information and applications  
write:  
Dr. J. D. Henry  
Department of Chemical Engineering  
West Virginia University  
Morgantown, West Virginia 26506



# CHEMICAL ENGINEERING

**DEGREES: M.S., Ph.D.**

**RESEARCH AREAS INCLUDE:**

- HEAT AND MASS TRANSFER
- REACTION KINETICS AND CATALYSIS
- PROCESS DYNAMICS AND CONTROL
- PROCESS MODELING

**IN:** COAL GASIFICATION, WOOD PYROLYSIS, METHANATION, ECOSYSTEM ANALYSIS, AND THEORETICAL STUDIES

**CONTACT: DR. WILLIAM J. HATCHER, JR., HEAD**  
P. O. Box 6312  
University, Alabama 35486

## AUBURN UNIVERSITY

A Land Grant University of Alabama

### GRADUATE STUDY IN CHEMICAL ENGINEERING

M.S. and PH.D. DEGREES

**CURRENT RESEARCH AREAS:**

- LIQUID FUELS FROM COAL
- POROUS MEDIA
  - CRYSTAL GROWTH KINETICS
  - INDUSTRIAL WASTEWATER TREATMENT
- PROCESS CONTROL
- P-V-T RELATIONS
- SOLIDS-LIQUID SEPARATION
- TRANSPORT PHENOMENA

**Financial Assistance:**

Research and Teaching Assistantships,  
Industrial Fellowships Are Available

**For Further Information, Write:**

Head, Chemical Engineering Department  
Auburn University, Auburn, Alabama 36830



DEPARTMENT OF CHEMICAL ENGINEERING

# BUCKNELL UNIVERSITY

LEWISBURG, PENNSYLVANIA 17837

For admission, address

**Dr. Paul H. DeHoff**

**Coordinator of Graduate Studies**

- Graduate degrees granted: Master of Science in Chemical Engineering
- Some courses for graduate credit are available in the evenings.
- Typical research interests of the faculty include the areas of: mass transfer, particularly distillation, solid-liquid, and liquid-liquid extraction; thermodynamics; reaction kinetics; catalyst deactivation; process dynamics and control; metallurgy and the science of materials; mathematical modeling; numerical analysis; statistical analysis.
- Assistantships and scholarships are available.
- For the usual candidate, with a B.S. in Chemical Engineering, the equivalent of thirty semester-hours of graduate credit including a thesis is the requirement for graduation.

## UNIVERSITY OF CALIFORNIA, DAVIS

### CHEMICAL ENGINEERING, M.S. AND PH.D. PROGRAMS

#### Faculty

R. L. Bell:	Mass Transfer, Bio Medical Engineering
R. G. Carbonell	Enzyme Kinetics, Quantum Mechanics
A. P. Jackman:	Process Dynamics, Thermal Pollution
B. J. McCoy:	Molecular Theory, Transport Processes
J. M. Smith:	Water Pollution, Reactor Design
S. Whitaker:	Fluid Mechanics, Interfacial Phenomena

#### To Receive Applications for Admission and Financial Aid Write To:

Graduate Student Advisor  
Department of Chemical Engineering  
University of California  
Davis, California 95616



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## CHEMICAL AND NUCLEAR ENGINEERING

Henri J. Fenech  
Husam Guroi  
Owen T. Hanna  
Duncan A. Mellichamp

Orville C. Sandall

John E. Myers  
G. Robert Odette  
A. Edward Profio  
Robert G. Rinker

For information, please write to: Department of Chemical and Nuclear Engineering  
University of California, Santa Barbara 93106

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Inquiries to: Dr. David B. Greenberg, Head  
Dept. of Chemical & Nuclear Engineering  
University of Cincinnati  
Cincinnati, Ohio 45221



# CLEMSON UNIVERSITY

Chemical Engineering Department

M.S. and Doctoral Programs

## THE FACULTY AND THEIR INTERESTS

Alley, F. C., Ph.D., U. North Carolina—Industrial Pollution Control  
Barlage, W. B., Ph.D., N. C. State—Transfer Processes in Non-Newtonian Fluids, Interfacial Phenomena  
Beard, J. N., Ph.D., L.S.U.—Digital Computer Process Control, Textile Dyeing and Finishing  
Beckwith, W. F., Ph.D., Iowa State—Transport Phenomena, Pulp and Paper Processing  
Eddie, D. D., Ph.D., U. Virginia—Crystallization, Polymer Processing  
Harshman, R. C., Ph.D., Ohio State—Kinetics and Reactor Design, Membrane Processes  
Melsheimer, S.S., Ph.D., Tulane—Membrane Transport, Numerical Methods, Process Control  
Mullins, J. C., Ph.D., Georgia Tech—Thermodynamics, Adsorption

**FINANCIAL ASSISTANCE**—Fellowships, Assistantships, Traineeships

Contact:

D. D. Edie, Graduate Coordinator  
Department of Chemical Engineering  
Clemson University  
Clemson, S. C. 29631

**the  
university  
of  
connecticut**

## faculty

J. P. BELL  
C. O. BENNETT  
M. B. CUTLIP  
A. T. DIBENEDETTO  
G. M. HOWARD  
H. E. KLEI  
R. M. STEPHENSON  
L. F. STUTZMAN  
D. W. SUNDSTROM

## programs

M.S. and Ph.D. programs covering most aspects of Chemical Engineering.

Research projects concentrate in four main areas:

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**financial aid** — Research and Teaching Assistantships, Fellowships

**location** — Beautiful setting in rural Northeast Connecticut, convenient to Boston, New York, and Northern New England

We would like to tell you much more about the opportunities for an education at UCONN, please write to:

Graduate Admissions Committee  
Department of Chemical Engineering  
The University of Connecticut  
Storrs, Connecticut 06268

# THE CLEVELAND STATE UNIVERSITY



## MASTER OF SCIENCE PROGRAM IN CHEMICAL ENGINEERING

---

### AREAS OF SPECIALIZATION

**Kinetics**

**Pollution Control**

**Simulation Processes**

The program may be designed as terminal or as preparation for further advance study leading to the doctorate. Financial assistance is available.

---

### FOR FURTHER INFORMATION, PLEASE CONTACT:

Department of Chemical Engineering  
The Cleveland State University  
Euclid Avenue at East 24th Street  
Cleveland, Ohio 44115

# Graduate Study in Chemical Engineering KANSAS STATE UNIVERSITY

M.S. and Ph.D. programs in Chemical Engineering and Interdisciplinary Areas of Systems Engineering, Food Science, and Environmental Engineering.

#### **Financial Aid Available**

Up to \$5,000 Per Year

#### **FOR MORE INFORMATION WRITE TO**

Professor B. G. Kyle  
Department of Chemical Engineering  
Kansas State University  
Manhattan, Kansas 66502

#### **AREAS OF STUDY AND RESEARCH**

DIFFUSION AND MASS TRANSFER  
HEAT TRANSFER  
FLUID MECHANICS  
THERMODYNAMICS  
BIOCHEMICAL ENGINEERING  
PROCESS DYNAMICS AND CONTROL  
CHEMICAL REACTION ENGINEERING  
MAGNETOHYDRODYNAMICS  
SOLID MIXING  
DESALINATION  
OPTIMIZATION  
FLUIDIZATION  
PHASE EQUILIBRIUM

# LEHIGH UNIVERSITY

Department of Chemical Engineering  
Whitaker Laboratory, Bldg. 5  
Bethlehem, Pa. 18015

Can you match the professor with his technical specialty(ies)?

PROFESSOR

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Curtis W. Clump  
Robert W. Coughlin  
Mohamed El-Aasser  
Alan S. Foust  
William L. Luyben  
Anthony J. McHugh  
Gary W. Poehlein  
William E. Schiesser  
Leslie H. Sperling  
Fred P. Stein  
Leonard A. Wenzel

RESEARCH/TECHNOLOGY

Mass and Heat Transfer  
Thermodynamics  
Energy/Fossil Fuels  
Nuclear Technology  
Polymer Materials Science  
Numerical Integration  
Catalysis  
Chemical Reactor Engineering  
Fermentation and Biochemical Engineering  
Enzyme Technology  
Cryogenics  
Process Design  
Technology Transfer  
Process Dynamics  
Waste Water Treatment  
Air Pollution Control  
Rheology  
Emulsion Polymerization  
Computer Simulation  
Surface Science  
Process Control  
Transport Phenomena  
Kinetics

# LSU

Graduate Enrollment — 60

Faculty — 19

- Bioengineering
  - Pollution Control
    - Process Dynamics
      - Computer Control
        - Kinetics and Catalysis
          - Thermodynamics
            - Ecological Modeling
              - Sugar Technology

Write: Chemical Engineering Department  
Louisiana State University  
Baton Rouge, Louisiana 70803

# McMASTER UNIVERSITY

Hamilton, Ontario, Canada  
M. ENG. & PH.D. PROGRAMS

## THE FACULTY AND THEIR INTERESTS

R. B. Anderson (Ph. D., Iowa)	Catalysis, Adsorption, Kinetics
M. H. I. Baird (Ph.D., Cambridge)	Oscillatory Flows, Transport Phenomena
A. Benedek (Ph.D., U. of Washington)	Wastewater Treatment, Novel Separation Techniques
J. L. Brash (Ph.D., Glasgow)	Polymer Chemistry, Use of Polymers in Medicine
C. M. Crowe (Ph.D., Cambridge)	Optimization, Chemical Reaction Engineering, Simulation
Y. Doganoglu (Ph.D., McGill)	Fluid Mechanics, Transport Processes
I. A. Feuerstein (Ph.D., Massachusetts)	Biological Fluid and Mass Transfer
A. E. Hamielec (Ph.D., Toronto)	Polymer Reactor Engineering, Transport Processes
T. W. Hoffman (Ph.D., McGill)	Heat Transfer, Chemical Reaction Engr., Simulation
J. F. MacGregor (Ph.D., Wisconsin)	Statistical Methods in Process Analysis, Computer Control
K. L. Murphy (Ph.D., Wisconsin)	Wastewater Treatment, Physicochemical Separations
L. W. Shemilt (Ph.D., Toronto)	Mass Transfer, Corrosion
W. J. Snodgrass (Ph.D., U. of N. Carolina, Chapel Hill)	Modelling of Aquatic Systems
J. Vlachopoulos (D.Sc., Washington U.)	Polymer Rheology and Processing, Transport Processes
D. R. Woods (Ph.D., Wisconsin)	Interfacial Phenomena, Particulate Systems
J. D. Wright (Ph.D., Cambridge)	Process Simulation and Control, Computer Control

DETAILS OF FINANCIAL ASSISTANCE AND ANNUAL RESEARCH REPORT AVAILABLE UPON REQUEST

CONTACT: Dr. A. E. Hamielec, Chairman,  
Department of Chemical Engineering  
Hamilton, Ontario, Canada L8S 4L7



## THE UNIVERSITY OF MICHIGAN CHEMICAL ENGINEERING GRADUATE PROGRAMS on the ANN ARBOR CAMPUS

The University of Michigan awarded its first Chemical Engineering M.S. in 1912 and Ph.D. in 1914. It has moved with the times since and today offers a flexible program of graduate study that allows emphases ranging from fundamentals to design.

The Chemical Engineering Department, with 21 faculty members and some 65 graduate students, has opportunities for study and research in areas as diverse as: thermodynamics, reactor design, transport processes, mathematical and numerical methods, optimization, mixing, rheology, materials, bioengineering, electrochemical engineering, production-pipelining-storage of oil and gas, coal processing, and pollution control.

The M.S. program may be completed in 10 months and does not require a thesis. The Professional Degree requires thirty-hours beyond the Master's and a professional problem. The Ph.D. program has recently been revamped to expedite entry into a research area as early in the program as possible.

For further information and applications, write:

Prof. Brice Carnahan  
Chairman of the Graduate Committee  
The University of Michigan  
Department of Chemical Engineering  
Ann Arbor, Michigan 48104

# MICHIGAN TECHNOLOGICAL UNIVERSITY



**DEPARTMENT OF CHEMISTRY  
AND CHEMICAL ENGINEERING**  
HOUGHTON, MICHIGAN 49931

## CHEMICAL ENGINEERING FACULTY

H. El Khadem, D. Sc. Tech.,  
Department Head

DEGREES GRANTED: M.S.

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L. B. HEIN, Ph.D. — Unit Operations, Mineral Extraction  
D. W. HUBBARD, Ph.D. — Lake Studies, Mixing Phenomena, Turbulent Flow  
J. T. PATTON, Ph.D. — Biosynthesis, Waste Treatment, Petroleum Recovery  
A. J. PINTAR, Ph.D. — Energy Conversion, Transport Phenomena, Applied Mathematics  
J. M. SKAATES, Ph.D. — Fluid-Solid Reactions, Catalysis, Reactor Design  
E. T. WILLIAMS, Ph.D. — Improvement of Pulpwood Yield

Financial assistance available in the form of Fellowships and Assistantships.

For more information, write to:

H. El Khadem, Head  
Department of Chemistry and Chemical Engineering  
MICHIGAN TECHNOLOGICAL UNIVERSITY  
HOUGHTON, MICHIGAN 49931

## **DO YOU THINK OF MINNESOTA**

- . . . as an hyperborean haunt of horrendous weather far to the north of the Cote d'Azur and other balmy latitudes?
- . . . as a domain dominated by dismal theoreticians and other weird species?

### **IF SO**

- . . . you're wrong on both counts. Our weather is brisk, to be sure, but far from glacial. Our theoreticians are doughty not dismal; and anyway the experimentalists outnumber the theoreticians—nor do they themselves fear theory.

**For the unexpurgated truth on graduate work at Minnesota, write:**

**DIRECTOR OF GRADUATE STUDIES**

**Department of Chemical Engineering & Materials Science  
University of Minnesota, Minneapolis, MN 55455**

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## DEPARTMENT OF CHEMICAL ENGINEERING

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

### Research Areas

Air Pollution Monitoring and Control

Biochemical Engineering and Biological Stabilization of Waste Streams

Biomedical Engineering

Catalysis

Energy Sources and Systems

Environmental Control Engineering

Heat and Mass Transport Influence by Fields

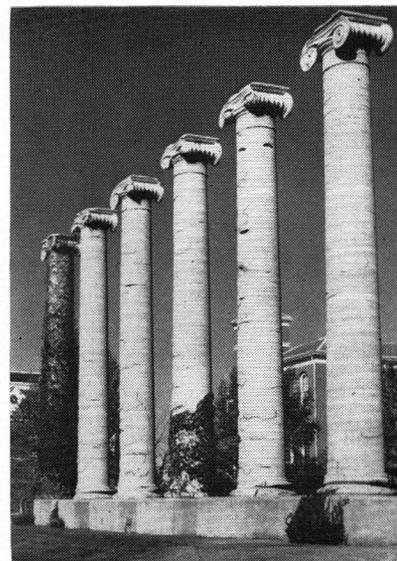
Newtonian and Non-Newtonian Fluid Mechanics

Process Control and Modelling of Processes

Single-Cell Protein Research

Thermodynamics and Transport Properties of Gases and Liquids

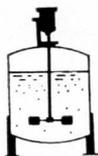
Transport in Biological Systems



**WRITE: Dr. George W. Preckshot, Chairman, Department of Chemical Engineering, 1030 Engineering Bldg., University of Missouri, Columbia, MO 65201**



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OFFERING GRADUATE STUDY AND RESEARCH  
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**Computer Applications**  
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**Kinetics**

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**Thermodynamics**  
**Tray Efficiencies and Dynamics**  
**and other areas**

FOR APPLICATIONS AND INFORMATION ON  
FINANCIAL ASSISTANCE WRITE TO:

**Prof W. A. Scheller, Chairman, Department of Chemical Engineering**  
**University of Nebraska, Lincoln, Nebraska 68508**



## **THE UNIVERSITY OF NEW MEXICO**

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**Radioactive Waste Management**  
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**Chairman**  
**Dept. of Chemical and Nuclear Engineering**  
**The University of New Mexico**  
**Albuquerque, New Mexico 87131**

## **STATE UNIVERSITY OF NEW YORK AT BUFFALO**

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

#### **Faculty and research interests:**

J. A. Bergantz	energy sources, gas-solid reactions
D. R. Brutvan	staged operations
H. T. Cullinan, Jr.	multicomponent mass transfer, transport properties
P. Ehrlich	polymeric materials, thermodynamics
W. N. Gill	dispersion, reverse osmosis
R. J. Good	surface phenomena, adhesion of living cells
K. M. Kiser	blood flow, turbulence, pollution in lakes
P. J. Phillips	polymer morphology, structure and properties
W. H. Ray	optimization, polymerization reactors
E. Ruckenstein	catalysis, interfacial phenomena, bioengineering
J. Szekely	process metallurgy, gas-solid and solid-solid reactions
T. W. Weber	process control, dynamics of adsorption
S. W. Weller	catalysis, catalytic reactors

**Financial aid is available**

**For full information and application materials, please contact:**

**Dr. Harry T. Cullinan, Jr.**  
**Chairman, Department of Chemical Engineering**  
**State University of New York at Buffalo**  
**Buffalo, New York 14214**

## THE NORTH CAROLINA STATE UNIVERSITY AT RALEIGH

offers programs leading to the M.S., M.Ch.E. and Ph.D. degrees in chemical engineering. Active research programs leading to approximately 50 journal publications per year are offered in all classical and contemporary research areas of chemical engineering. The proximity of a large number of polymer-related research facilities at the nearby Research Triangle Park and the various offices and laboratories of the Environmental Protection Agency in and near the Park stimulates strong research programs in polymers and air pollution technology at North Carolina State University. Graduate students are further stimulated by beaches and mountains, an early spring and a late fall, and the sister universities of Duke and UNC Chapel Hill. Our distinguished senior faculty of K. O. Beatty Jr., J. K. Ferrell, H. B. Hopfenberg, Warren L. McCabe, E. M. Schoenborn, E. P. Stahel and V. T. Stannett join their colleagues in inviting your application to study chemical engineering in North Carolina.



# THE UNIVERSITY OF OKLAHOMA

WRITE TO:  
THE SCHOOL OF CHEMICAL ENGINEERING  
AND MATERIALS SCIENCE

The University of Oklahoma  
Engineering Center  
202 W. Boyd Room 23  
Norman, Oklahoma 73069

- CATALYSIS
- CORROSION
- DIGITAL SYSTEMS
- DESIGN
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- METALLURGY
- THERMODYNAMICS
- RATE PROCESSES
- ENZYME TECHNOLOGY

# GRADUATE STUDY IN CHEMICAL ENGINEERING

## THE OHIO STATE UNIVERSITY

### M.S. AND Ph.D. PROGRAMS

- Environmental Engineering
  - Reaction Kinetics
    - Heat, Mass and Momentum Transfer
    - Nuclear Chemical Engineering
      - Rheology
        - Energy Sources and Conversion
          - Optimization and Advanced Mathematical Methods
          - Biomedical Engineering and Biochemical Engineering
- Process Analysis, Design and Control
  - Polymer Engineering
    - Petroleum Reservoir Engineering
      - Thermodynamics
        - Unit Operations
          - Process Dynamics and Simulation

**Graduate Study Brochure Available On Request**

**WRITE: Aldrich Syverson, Chairman**  
**Department of Chemical Engineering**  
**The Ohio State University**  
**140 W. 19th Avenue**  
**Columbus, Ohio 43210**

## Princeton University

### M.S.E. AND Ph.D. PROGRAMS IN CHEMICAL ENGINEERING

#### FACULTY

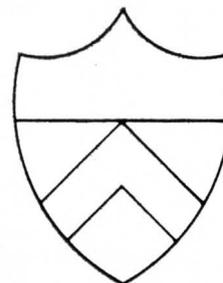
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Robert C. Axtmann  
Robert L. Bratzler  
Joseph M. Calo  
John K. Gillham  
Ernest F. Johnson  
Morton D. Kostin  
Leon Lapidus  
Bryce Maxwell  
David F. Ollis  
William B. Russel  
Dudley A. Saville  
William R. Schowalter  
Garth L. Wilkes

#### RESEARCH AREAS

Atmospheric Aerosols  
Bioengineering  
Catalysis  
Chemical Reactor/Reaction Engineering  
Computer-Aided Design  
Energy Conversion & Fusion Reactor Technology  
Environmental Studies  
Fluid Mechanics & Rheology  
Mass & Momentum Transport  
Molecular Beams  
Polymer Materials Science & Rheology  
Process Control & Optimization

#### WRITE TO

**Director of Graduate Studies**  
**Chemical Engineering**  
**Princeton University**  
**Princeton, New Jersey 08540**





ENERGY RESOURCE RESEARCH  
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MEMBRANE TECHNOLOGY  
PROCESS DYNAMICS

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or Ph.D. in chemical engineering.

Graduate Coordinator  
Chemical/Petroleum Engineering  
University of Pittsburgh  
Pittsburgh, Pa. 15261

# University of Pittsburgh

**Queens University**  
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## Graduate Studies in Chemical Engineering

MSc and PhD Degree Programs

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H.A. Becker Sc.D. (MIT)  
D.H. Bone Ph.D. (London)  
S.C. Cho Ph.D. (Princeton)  
R.H. Clark Ph.D. (Imperial College)  
R.K. Code Ph.D. (Cornell)  
J. Downie Ph.D. (Toronto)  
J.E. Ellsworth Ph.D. (Princeton)  
C.C. Hsu Ph.D. (Texas)  
J.D. Raal Ph.D. (Toronto)  
T.R. Warriner Sc.D. (Johns Hopkins)  
B.W. Wojciechowski Ph.D. (Ottawa)

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water and waste treatment  
applied microbiology  
biochemical engineering
- Chemical Reaction  
Engineering  
catalysis  
statistical design  
polymer studies
- Transport Processes  
combustion  
fluid mechanics  
thermodynamics

Write:

Dr. John Downie  
Department of Chemical  
Engineering  
Queen's University  
Kingston, Ontario  
Canada



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AND  
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POLYMER PROCESSING  
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SOLID WASTES

**Rensselaer Polytechnic Institute**, established in 1824 "for the application of science to the common purposes of life," has grown from a school of engineering and applied science into a technological university, serving some 3500 undergraduates and over 1000 graduate students.

It is located in Troy, New York, about 150 miles north of New York City and 180 miles west of Boston. Troy, Albany, and Schenectady together comprise the heart of New York's Capital District, an upstate metropolitan area of about 600,000 population. These historic cities and the surrounding countryside provide the attractions of both urban and rural life.

Scenic streams, lakes and mountains, including the Hudson River, Lake George, the Green Mountains of Vermont, the Berkshires of Massachusetts, and portions of the Adirondack Forest Preserve, are within easy driving distance, and offer many attractions for those interested in skiing, hiking, boating, hunting, fishing, etc.

**For full details write**

**Mr. R. A. Du Mez, Director of Graduate Admissions,  
Rensselaer Polytechnic Institute, Troy, New York**

**12181.**



**Canada's largest Chemical Engineering Department offers M.A.Sc., Ph.D. and post-doctoral programs in:**

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- \* **Environmental and Pollution Control**
- \* **Extractive and Process Metallurgy**
- \* **Polymer Science and Engineering**
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- \* **Transport Phenomena and Kinetics**

**Financial Aid:** Competitive with any other Canadian University

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**To apply, contact:**

**The Associate Chairman (Graduate Studies)  
Department of Chemical Engineering  
University of Waterloo  
Waterloo, Ontario  
Canada N2L 3G1**

**Further information:** See CEE, p. 4, Winter 1975

CHEMICAL ENGINEERING  
GRADUATE STUDY IN  
**SYRACUSE UNIVERSITY**

RESEARCH AREAS

Water Renovation	Transport Phenomena
Biomedical Engineering	Separation Processes
Membrane Processes	Mathematical Modeling
Desalination	Rheology

FACULTY

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