



chemical engineering education

CHEMICAL ENGINEERING DIVISION OF AMERICAN SOCIETY FOR ENGINEERING EDUCATION

FALL 1970

GRADUATE EDUCATION ISSUE

BERG Interfacial Phenomena
BOUDART Kinetics
KOPPEL Process Control
LEONARD Bioengineering
LICHT Air Pollution
METZNER & DENN Fluid Mechanics
POWERS Separation Processes
TOOR & CONDIFF . . . Heat & Mass Transfer
TSAO Biochemical Engineering

"Doc"
Lewis
OF MIT



AICHE President
CONN on
Management

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As a senior you may be asking some of the questions below about graduate school. CEE in this issue as in the fall 1969 issue attempts to assist you in finding answers to them.

A LETTER TO CHEMICAL ENGINEERING SENIORS

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 that greatly enhances your ability to obtain responsible and challenging positions in industry and teaching. 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. At the same time, we recognize that while a graduate degree may lead to either technical work or to management, some of you may wish to work directly toward careers in management. To acquaint you with this option, we invite you to read the article on this subject by AIChE President, Art Conn.

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 we began last year of featuring articles on graduate courses as they are taught by scholars at various universities. Last year's issue included articles on applied mathematics, momentum and energy transfer, reactor design, fluid dynamics, particulate systems, optimal control, diffusional operations, and thermodynamics. This year we are eliminating some of these in order to emphasize certain specialized areas that were not included in last year's issue 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 last year. 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.

What is the nature of chemical engineering graduate research?

One way in which you can obtain an answer to this question is to read papers in the technical publications; but another way you may obtain insight into graduate research is to learn something about the people who are outstanding chemical engineering scholars. To assist you in doing so we are again this year including an article on one of the "Founders of Chemical Engineering," Dr. W. K. Lewis of the Massachusetts Institute of Technology. Dr. Lewis has not only made numerous significant contributions to the literature, but he has also had an enormous impact on his students—many of whom have themselves become leaders in the profession.

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 to choose among, 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. Or 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. Or 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 hope that you explore the possibility of continuing your education in graduate school.

Sincerely,

RAY FAHIEN, Editor CEE
University of Florida
Gainesville, Florida 32601

DEPARTMENT CHAIRMEN: We regret we were unable to satisfy all requests for free copies. Please see p. 240.



"Doc" Lewis of MIT

Few men have had a greater influence on his students — and/or the profession, — than Dr. Warren Kendall Lewis of Massachusetts Institute of Technology. This article was prepared for CEE by Professor E. R. Gilliland.

IN THE FALL of 1901 a farm boy from Delaware entered M.I.T. to study mechanical engineering but a year later, at the suggestion of one of his classmates whose family operated a tannery, he transferred to a new course called Chemical Engineering. For over sixty years Dr. Warren K. Lewis has had a leading role in the creation, development and growth of this new engineering discipline. He has been a profound influence on the whole profession and on many of its leaders.

Dr. Lewis was born on a farm near Laurel, Delaware, on August 21, 1882. After early schooling in Laurel, he transferred to high school in Newton, Massachusetts, and entered the Massachusetts Institute of Technology in 1901. He had planned to return to the farm, but following graduation Dr. William H. Walker offered him an assistantship which he accepted.

The chemical industry was undergoing a major transformation at this time. The first syntheses of rayon were struggling to solve their

industrialization difficulties. The advent of the automobile found the rubber industry with problems of producing tires with properties far exceeding those then obtainable in the rubber goods that had been produced, and petroleum refining was shifting to gasoline as its major product. M.I.T. had introduced a new educational program in the Chemistry Department in 1888 under the leadership of Professor Lewis M. Norton and named it Course X, Chemical Engineering. Norton died a few years later and in 1902 the Institute brought Dr. Walker from industry to head Course X.

In 1906, Dr. Lewis was awarded an M.I.T. fellowship for graduate work in Europe and he went to the University of Breslau, Germany, and studied physical chemistry under Abegg, receiving his Ph.D. in 1908. He returned to M.I.T. as a research associate in applied chemistry and then in 1909 joined the N. H. McElwain Company, a tannery in Merrimack, New Hampshire, as a chemist. Dr. Walker was successful again in attracting him to M.I.T. with an appointment as an Assistant Professor in 1910 and a full professorship followed in 1914.

In 1920 Course X was separated from the Chemistry Department and Dr. Lewis became the first head of the new department, a position he held until 1929 when he resigned to devote full time to his teaching.

Doc's career has covered many areas but his most important professional contributions were his leading role in the development of the profession of chemical engineering, his contributions to individual chemical and petroleum processes, his advice to students, associates, industry and government and his development of men.

FROM THE START of his teaching career, Dr. Lewis concentrated on utilizing the resources of basic knowledge in physical chemistry and physics to solve the engineering problems of chemical industry. He had an extraordinary understanding of basic science. He knew clearly the experimental facts that made him believe in atoms, in molecules, in kinetic theory, in forces between molecules and in the conservation of energy. His interest in and understanding of science and his ability to apply it was always a joy to behold. In tackling a new problem he

always went back to these fundamental concepts. Distillation, heat transfer, fluid flow and absorption were ripe for this treatment, and he soon developed an integrated complex of research and teaching which resulted in a concept known as Unit Operations. Chemical processes are many and varied, and the Unit Operations made it possible to have a systematic discipline for the design and engineering of these complex operations. This was an exciting era of exploration and constant change for Lewis and his assistants — a time of no text-books, when classroom notes became obsolete shortly after they were distributed. By 1923 the product of these years was

Doc's career has covered many areas but his most important professional contributions were his leading role in the development of the profession of chemical engineering, his contributions to individual chemical and petroleum processes, his advice to students, associates, industry, and government, and his development of men.

published by Walker, Lewis and McAdams as "Principles of Chemical Engineering" a text which profoundly stimulated the evolution of the profession.

He realized that while the applied physics and physical chemistry of the Unit Operations should be a strong component of chemical engineering that it alone was not a sufficiently broad base for those who were to be the leaders in the chemical profession. He believed that the special characteristic of a chemical engineer should be his understanding of chemistry and his ability to engineer it into industrial operations.

Leaving largely to others the further development of the Unit Operations, Lewis was soon engaged in introducing subjects in stoichiometry, industrial chemistry and in materials. In stoichiometry he enjoyed showing the student the great power of simple material and energy balances as tools for obtaining insight into a process. This work led to his book with Radasch on "Industrial Stoichiometry." His subjects in industrial chemistry were not descriptions of current practice, although he had a very broad knowledge of industry from his consulting work, but were instead detailed analyses of a limited number of industrial processes. Each step of a process was analyzed on the basis of the material and energy balances, the physical chemistry, the chemical kinetics, the unit operations, the rate limiting steps involved and the choice of equipment. He would have detailed discussions with the students on what alternatives were possible

and the pros and cons of each. Many of the discussions led to worthwhile innovations for the industrial operations. Professor Lewis recognized that materials, particularly non-metallic materials, were an important area for the future of chemical engineering, and soon after the publication of PCE he was engaged in formulating subjects on the basic principles involved in the understanding of surface chemistry and physics and of colloidal and amorphous materials such as gels, clays, textiles, plastics, leather, paper and rubber. This new material was quickly incorporated with the Unit Operations in both the undergraduate and graduate programs in chemical

engineering at M.I.T. and led to his book on "The Industrial Chemistry of Colloidal and Amorphous Materials."

HE WAS A superb teacher both as a lecturer and in the classroom. His lectures were beautifully organized and he had an unforgettable and unlimited supply of stories to illustrate all key points, but his greatest enjoyment was to challenge the students, or his colleagues, or anyone who would listen on some problem or principle. One of his favorite techniques for developing creativity in his students and the habit of defending their ideas was his famous "dollar to doughnut" bets. He admired the man who had ideas and who would defend them as long as he was convinced they were correct. A number of Doc's stories and quotes were collected and published some years ago in a volume entitled "Dollars to Doughnuts."

Dr. Lewis has always been an enthusiastic and prolific inventor and has received over 80 patents on his inventions, many of which have been widely applied in the chemical and petroleum industries. He attacks all problems with the viewpoint that there is a better solution, and proceeds to develop such a solution on the basis of clear and simple pictures of the fundamental relationships involved.

Dr. Lewis began consulting with industry early in his career under the guidance of Dr. Walker. While Dr. Walker had emphasized the necessity of basic science as the foundation of chemical engineering he believed that it was vital

for an engineer to understand and to be involved in industrial practice. He himself was an active industrial consultant to the chemical industry and for a number of years Walker was a partner with A. D. Little in the consulting firm of Little and Walker.

Before World War I, Doc was working with Goodyear and Standard Oil Company of New Jersey. At Goodyear he did both consulting work and gave courses to the research group on applied physical chemistry, chemical engineering and materials. At this time the field of macromolecules was a maze of empirical knowledge although some of the bases of the modern interpretations had already been suggested. Working with the men in the Goodyear chemical department, he stimulated the development of a coherent working hypotheses of the structure and behavior of macromolecules, which was helpful in guiding the development of rubber technology. His work correlated the confused theories as to the nature of rubber and showed the relationships between the macromolecules of rubber and similar ones encountered in leather, cellulose, and other materials.

FOR MORE THAN forty-five years he has been a consultant to Humble Oil and Refining Company and the Esso Research and Engineering Company (formerly Standard Oil Development Co.) both of which are affiliates of Standard Oil Company (N.J.) One of his first contributions was an improved method for the vacuum distillation of lubricating oils in which he showed the advantage of reducing the resistance to flow of the vapor from the evaporating liquid to the condenser. He worked with Professor A. A. Noyes on an analysis of Sorel's and Hausbrand's work on the rectification of alcohol and saw the potentialities for such an operation in many chemical and petroleum separations. He was responsible for the first large scale application of continuous rectification in the petroleum industry: an installation of columns on a series of shell stills for the sharp separation of naphthas and gas oils. He later played a leading role in the development of the pipe still and in the development of super fractionators for the preparation of components for synthetic rubber and aviation gasoline.

Dr. Lewis was actively involved in petroleum cracking developments. In thermal cracking, coke formation was a troublesome problem because it would frequently deposit at a rapid

Doc as the prime factor in the professional development of many men who are now leaders in the chemical and petroleum industries.

rate in localized regions and stop the operation. He formulated models for the formation of coke by the cracking operation indicating that the reactions involved the production of active species which condensed, re-cracked and by a repetition of this cycle led to coke. Understanding that some basic steps of this reaction sequence were higher than first order, he proposed that the localized production of coke was due to the concentration of active species in these areas and that by mechanical design and by conditions that would dilute and rapidly wash out these constituents the coke problem could be licked.

The work on thermal cracking and on reservoir engineering and petroleum production led to his pioneering studies on the high pressure vapor-liquid equilibria, in both the P-V-T and interphase equilibrium constant areas. His work on petroleum production also led to his investigations of two-phase liquid flow through porous media which he integrated with his work on inter-facial surface properties that had developed in his surface chemistry and physic subjects

Prior to 1938 it was difficult to carry out heterogeneous reactions between gases and solids in those cases where large energy effects were involved or in which the solid rapidly deactivated and needed frequent regeneration. A number of important reactions were limited in this way and required expensive reactor construction and complicated operating procedures. For example, it had been known for many years that silica-alumina catalysts were effective for the cracking of hydrocarbons and that the products had higher octane numbers than those obtained from conventional processes. However, it was difficult to make the operation practical because, first, the catalyst deactivated rapidly due to carbon deposition, and second, the cracking operation was highly endothermic, while the catalyst regeneration stage, i.e., burning the carbon off the catalyst, was highly exothermic. Frequent and complicated cycles were involved to maintain adequate catalyst activity and to prevent explosion by the mixing of oxidizing gas and the hydrocarbons. In addition complicated reactor designs were employed in order to supply heat during the reaction cycle and to remove heat during the regeneration cycle. The complications of the cycles

were such that they were made longer than desirable, resulting in lower average catalyst activity.

DR. LEWIS pioneered the fluidized powdered solid system which was a much more effective method of handling such reactions. By fluidizing the solid and producing a system that could flow like a fluid, it was possible to pass the catalyst rapidly between a reaction zone and a regeneration zone thereby maintaining high average catalyst activity within the reactor. Likewise, the rapid flow of catalyst from the regenerator to the reactor made it possible to carry heat from one vessel to the other by the sensible heat of the solid, thereby eliminating

allied Conference on Gas Warfare. In 1940 — eighteen months before Pearl Harbor — Dr. Lewis joined the National Defense Research Committee (later OSRD) organized by Vannevar Bush, J. B. Conant, and Roger Adams for the attack on technical problems of concern to the military. He was also a member of the Senior Advisory Committee for the Manhattan Project.

Doc has been the prime factor in the professional development of many men who are now leaders in the chemical and petroleum industries. His teaching and his interest and success in the development of men trained to think creatively and practically in the field of applied-chemistry reveal his full character. Those who

Doc has always been an enthusiastic and prolific inventor . . . He attacks all problems with the viewpoint that there is a better solution . . . Dr. Lewis pioneered the fluidized powdered solid system.

any heat transfer through the walls. In addition, rapid mixing within the fluidized bed gave almost complete uniformity of temperature in both the reactor and the regenerator.

The process was so outstanding in its advantages that the type of reactor previously employed for catalytic cracking was abandoned within a relatively few years. The fluidized process was developed just as World War II was beginning and accounted for a large fraction of the aviation gasoline produced by the United States. The fluidized solid operation has outstanding advantages for heterogeneous reactions involving large heat effects or whenever it is desirable to move solids through the reaction zone rapidly, and as a result has been applied to the coking of heavy petroleum residues, hydroforming of naphtha, burning of limestone, processing of sulfide ores, production of silicones, oxidation of naphthalene, and many other chemical reactions. It has probably had a more rapid and extensive adoption than any other chemical engineering process technique in recent years, and, at the present time, the capital investment represented by the fluidized processes is several billion dollars.

Dr. Lewis was extensively involved with the government during both World Wars. During the first war he was active with the Chemical Warfare Service and the Bureau of Mines and was in charge of the development program for gas defense. In October 1918 he represented the Chemical Warfare Service at the Paris Inter-

have been associated with him in the classroom, in research projects, and in industrial work consider this experience one of the most important and exciting parts of their professional career. Many of these men are now teaching and twelve of his former students have been elected to the National Academy of Engineering and six to the National Academy of Sciences. The success and contributions of these former students are his greatest satisfaction.

The characteristics that made Dr. Lewis outstanding as a teacher and builder of men were a tireless devotion to his work and to his ideals, a rare form of modesty in giving credit to others, sympathy for the man who made an effort (excellence preferred) but the effort was paramount, a wonderful enthusiasm for his profession and for tackling the tough problems, for making chemical engineering practice a vivid and colorful experience, and a knack for teaching and for inspiring the best in his students and associates.

THE CONTRIBUTIONS Dr. Lewis has made have been recognized by many honors and awards. He has received honorary doctorate degrees from the University of Delaware, Princeton University, Harvard University and Bowdoin College. He has received the President's Medal of Science and the President's Medal of Merit. He was honored by AIChE by the establishment of the Warren K. Lewis Award jointly sponsored by the Esso Research and Engineering Company and the Humble Oil and Refining Company which

recognizes outstanding educators in chemical engineering. He has received the Perkins Medal of the Society of Chemical Industry, American Section (1936); the Lamme Medal of ASEE (1947); the Priestley Medal of the ACS (1947); the Gold Medal of the American Institute of Chemists (1949); the New England Award of the Engineering Societies of New England (1950); the Industrial and Engineering Chemistry Award of the ACS (1956); the API Gold Medal for Distinguished Achievement (1957); the John Fritz Medal given jointly by the five national engineering societies (1966) and the Founders Award of the AIChE (1958). In 1969 the faculty, friends and alumni of Course X established through contributions the Warren K. Lewis Professorship in Chemical Engineering at M.I.T.

At 88 years of age, Doc is still vigorous and active and willing to give anyone a lecture (and his solution) on technical or social problems.

He continues to be an inspiration for those who were associated with him and the chemical engineering profession has been very fortunate in having one of the outstanding teachers and engineers of the century in its rank.

ChE book reviews

Molecular Thermodynamics of Fluid-Phase Equilibria. J. M. Prausnitz, Prentice-Hall, New York (1969).

For those chemical engineers (and chemists) who wish a succinct evaluation of this book then I recommend you buy it! It provides an excellent, up-to-date reference source to allow one to interpret and correlate phase equilibrium data—and, in many cases to predict phase compositions *a priori* from theory.

A more detailed review should, of course, note the style, degree of clarity, aptness, and content. The first three of these attributes need little comment. The book is very well written, extremely easy to follow, and treats a subject which is of great import to the chemical engineering profession.

Regarding the content, two points seem worth noting, both of which are covered in the preface. First, Professor Prausnitz states that in the book, "no attempt has been made to be exhaustive." Topics were selected with which he was familiar and topics such as metal or electrolyte solutions were not considered. The point to be made here

is, however, that in the material covered, it appears to the reviewer, that for solutions of organic materials, a very fair appraisal has been presented and the material well documented in the bibliography.

The second point to emphasize is the general philosophy of the book wherein the author defines his approach to the study of phase equilibria as one of "an engineering science, based on classical thermodynamics but relying on molecular physics and statistical thermodynamics to supply insight into the behavior of matter. In application, therefore, molecular thermodynamics is rarely exact; it must necessarily have an empirical flavor."

This latter statement sets the tone of the entire book. When it is possible to be rigorous, one finds a clear derivation of the significant relations. When such an approach is not possible, empiricism is introduced, but in a manner to try and extract generalizations from specific cases so as to allow the reader himself to extrapolate and interpolate and thus lead one to logical reasoning for different cases.

The first six chapters neatly condense those elements of thermodynamics necessary throughout the remainder of the book. In particular, emphasis has been correctly placed on the requirement for an accurate equation of state to obtain gas phase fugacities. Perhaps more emphasis could have been given to those mathematical difficulties encountered in obtaining liquid fugacities by integrating a fugacity expression across the two phase envelope, but this viewpoint is implied since the remainder of the book deals primarily with liquid phase models to determine activity coefficients. The straight-forward review of the principal concepts of intermolecular forces in Chapter 5 will be appreciated by most readers.

Chapters 6 and 7 treat excess functions and solution theories to allow one to handle liquid fugacities while Chapters 8 through 10 deal with the specific topics of the solubility of gases in liquids and solids and high pressure equilibria. Nine appendices are used to prevent detailed derivations from blocking the smooth flow of ideas in the text.

As a reference or as a class text, this book should be valuable for many years. Those active in the field might hope that this book might soon become obsolete. However, there is little chance of this occurring!

R. C. Reid
Massachusetts Institute of Technology

To a man with emphysema, a flight of stairs is Mt. Everest.



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It makes sense that if we can help a diver dive to 1000 feet, we can give a man with emphysema the air to get to the top of the stairs.



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A Course on Fluid Interfaces

INTERFACIAL PHENOMENA

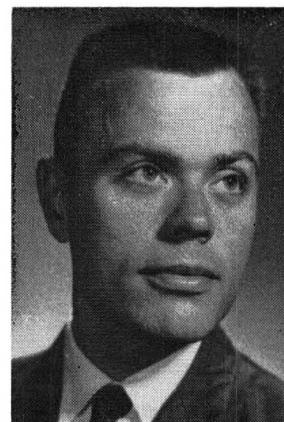
JOHN BERG

*University of Washington
Seattle, Washington 98105*

A WIDE VARIETY of topics involving fluid interfaces have, in the minds of chemical engineers, begun to coalesce into a single area of study which might be called "interfacial phenomena". This is occurring primarily for two reasons: first, the increasing recognition of the importance of interfacial effects in chemical engineering practice, and second, the increasing neglect of interfacial topics in conventional course sequences in chemistry and physics. These it seems are reasons not unlike those which gave birth to a unified study of the transport phenomena in chemical engineering.

The diversity of problems in the realm of interfacial phenomena is staggering. Space would not permit an attempt at a complete listing, but a small sample might include: wetting, spreading, foaming, colloid stability, sedimentation, interfacial turbulence, cellular convection, micelle formation, solubilization, detergent action, nucleation, flow through porous media, lung mechanics, structure of cell membranes, reactions in monolayers, evaporation suppression, adhesion, lubrication, mechanics of bubbles and drops, fluid phase catalysis, meniscus stability, adsorption kinetics and equilibria, surface rheology, active transport, and electrical double layers.

One feature which most interface problems have in common with each other is that, in addition to being problems in interfacial phenomena, they are also problems in one or more presently recognized fields of study, such as hydrodynamics, thermodynamics, statistical mechanics, physiology, electro-chemistry, etc. The resultant "crazy-quilt" nature of the subject of interfacial phenomena is evident in such books as Davies and Rideal (4), Adamson, (2), and Osipow, (9). With the partial exception of Davies and Rideal, a feature which most "comprehensive" books on the subject have in common is that they are written from the chemists' point of view. They often neglect topics of vital interest to the chemical engineer, particularly those involving the fluid



John Berg was educated at Carnegie Tech (B.S.) and University of California, Berkeley (Ph.D. '64). His research interests are in interfacial phenomena, in particular, the investigation of thermodynamic and transport properties of multicomponent interfaces, surface tension driven flows, and the surface chemistry of the lung. He is presently an associate professor at the University of Washington.

mechanics of interfaces and the consequent effects on heat and mass transfer. This material must be gathered from the relatively recent chemical engineering literature.

The problem facing one who would construct a course on interfacial phenomena for chemical engineers is to formulate the essential skeleton of fundamentals common to all fluid interface studies and to flesh-out this skeleton with sufficient examples to illustrate the principles. The pitfall to avoid is the presentation of a parade of examples with insufficient attention to the common ground between them.

SUMMARY OF PRESENT COURSE

A GRADUATE LEVEL course in Interfacial Phenomena is offered by the author at the University of Washington in alternate years and has thus far been given in the Spring quarters of 1968 and 1970. The course requires one quarter each of graduate level thermodynamics and fluid mechanics as prerequisites. Many of the problems of interfacial phenomena provide excellent opportunities to combine these generally non-intersecting disciplines. Although the specific content of the course differed significantly in its first and second offerings, and will change yet again in its subsequent offerings, a skeletal outline is presented in Table I. The course content is necessarily flexible to permit incorporation of the most recent research results obtained both in our

TABLE I
TOPICAL OUTLINE OF COURSE IN
INTERFACIAL PHENOMENA

- I. Surface Tension and Capillary Statics (2, ch. 1; 5, ch. 1)
 - A. The concept of surface tension; the "membrane model"
 - B. The equation of Young and Laplace
 - C. Meniscus configurations and contact angles. (3, ch. 5)
 - D. Measurement of static surface tension (1, ch 9)
 - E. Measurement of dynamic surface tension
 - F. Stability of static menisci (10)
 - G. The effect of curvature on the thermodynamic properties of bulk phases. (5, chs. 15-16)
- II. The Thermodynamics of Capillary Systems (5, chs. 1-7)
 - A. Definition of simple capillary systems
 - B. The Gibbs dividing surface
 - C. Relative adsorption and its direct measurement
 - D. First Law calculations for capillary systems; surface tension of pure components (5, ch. 11)
 - E. Fundamental equations for capillary systems
 - F. The Gibbs adsorption equation
- III. Thermodynamic Properties of Some Important Capillary Systems
 - A. Surface tension of simple solutions; the monolayer model (5, chs. 12-13)
 - B. Solutions of non-colloidal electrolytes
 - C. Solutions of surface active agents (1, ch. 3; 9, chs. 8-9)
 - D. Monolayers of insoluble surfactants (1, ch. 2; 6; 7)
 - E. A general phase rule for capillary systems (5, ch. 6)
- IV. Capillary Dynamics (8, chs. 7-8)
 - A. Boundary conditions at fluid interfaces
 - B. The Newtonian fluid interface
 - C. Surface transport properties (4, chs. 4-5)
 - D. Case study of circulating drops and bubbles
 - E. Case study of cellular convection and interfacial turbulence

group and elsewhere. No textbook is followed, but copious use of references is made. A few of the principle ones are inserted by number into the outline below and listed in Table II.

I. Capillary Statics

THE FIRST MAJOR area examined is "capillary statistics", i.e. the determination of static equilibrium configurations of fluid interfaces and the forces they exert on solids in contact with them. Following a preliminary discussion of the molecular nature of transition regions between bulk phases, the 'membrane model' of the mobile interface is presented. The position of the "membrane" (the "surface of ten-

Much of the material . . . lends itself to interesting and illuminating lecture or laboratory demonstration.

sion") and the value of the surface tension, σ , are chosen to make the model mechanically equivalent to the complex layer which is actually the interface. The model leads to the Young-Laplace equation: $\Delta p = 2\sigma\kappa_m$, where Δp is the pressure difference across the interface and κ_m its mean curvature. Following a discussion of the geometry of surfaces in space, the derivation is presented from both the force-balance and variational points of view. The force-balance derivation, in which the surface curvature is written as $1/r_1 + 1/r_2$, the sum of the two plane curvatures, has a simple physical appeal and lends itself well to the consideration of simpler special cases such as surfaces of axial or bilateral symmetry. The variational derivation can readily be extended (by examining the *second* variation of the systems' total potential energy) to a consideration of problems of meniscus stability.

The most important application of capillary statics is to the measurement of equilibrium surface tension. This is accomplished through the measurement of the position or shape of the fluid interface or of the force it exerts on a solid object imbedded in it. The capillary rise, maximum

TABLE II
SOME TEXTUAL REFERENCES ON
INTERFACIAL PHENOMENA

1. Adam, N. K., "The Physics and Chemistry of Surfaces," Dover (1968) (1941 edition).
2. Adamson, A. W., "Physical Chemistry of Surfaces," Interscience (1967).
3. Bickerman, J. J., "Surface Chemistry for Industrial Application," Academic Press (1947).
4. Davies, J. T. and E. K. Rideal, "Interfacial Phenomena," Academic Press (1961).
5. Defay, R., I. Prigogine, A. Bellemaus and D. H. Everett, "Surface Tension and Adsorption," Longmans (1966).
6. Gaines, G. L., "Insoluble Monolayers at Liquid-Gas Interfaces," Interscience (1966).
7. Harkins, W. D., "The Physical Chemistry of Surface Films," Reinhold (1952).
8. Levich, V. G., "Physicochemical Hydrodynamics," Prentice-Hall (1962).
9. Osipow, L. I., "Surface Chemistry," Reinhold (1962).
10. Satterlee, H. M. and W. C. Reynolds, "The Dynamics of the Free Liquid Surface," NSF Tech. Rep. LG-2 (1964).

The course requires one quarter each of graduate level thermodynamics and fluid mechanics. Many of the problems of interfacial phenomena provide excellent opportunities to combine these generally non-intersecting disciplines.

bubble pressure, drop weight and Wilhelmy slide methods are examined in some detail, and computer solutions of the Young-Laplace equation are used where applicable. Although not strictly studies in capillary statics, two methods for measurement of "dynamic" (i.e., time-dependent) surface tension are also described at this point: the oscillating elliptical jet and the contracting circular jet.

The unit is concluded with a discussion of the effect of curvature on the thermodynamic properties of bulk phases, in particular the altered vapor pressure of liquids in small capillaries or as fine droplets and the altered solubility of finely divided solids or finely dispersed liquids. The Young-Laplace equation gives the relationship between the pressure difference and curvature while the usual Poynting factor gives the effect of pressure change on the fugacity of the liquid or solid in question.

II. Thermodynamic Framework

THE SECOND PART of the course deals with the classical thermodynamics of capillary systems per se. A "simple capillary system" is defined as a pair of simple bulk phases together with the interface between them. Such a system is subject to p-V work associated with both the bulk phase parts and σ -A work associated with the interface. A state postulate is formulated for such systems in "partial equilibrium", as defined by Defay, et al (5). The system is taken to be in internal thermal and mechanical equilibrium (as defined by the Young-Laplace equation) but not necessarily in equilibrium with respect to chemical reactions or adsorption of components from the bulk phases to the interface. In order to define the amounts of adsorption of the various components, as well as other extensive properties to be associated with the interface itself, a model of the capillary system must be employed, such as that of the Gibbs dividing surface. The interface is replaced with a geometrical surface and the bulk phase portions of the system are assumed homogeneous up to this surface. Requiring thermodynamic equivalence between the actual system and the model defines quantities to be associated with the dividing surface as "surface ex-

cesses". The formal thermodynamics of capillary systems is developed using the Gibbs model, but the Guggenheim model (in which the interface is treated as a region of finite thickness, across which properties vary) and the monolayer model (in which the interface is treated as a single monolayer of molecules whose composition differs from that of both bulk phases) are also used in subsequent applications. The formulation based upon the Gibbs model is of course rigorous, but the surface excesses it defines are highly sensitive to the dividing surface location, which for plane surfaces is indeterminate. Therefore, *relative* adsorptions, whose values are invariant with respect to dividing surface location, are used. The cornerstone of the thermodynamics of capillary systems is the Gibbs adsorption equation, which provides a rigorous equilibrium relationship between relative adsorptions, surface tension, and bulk phase chemical potentials.

III. Thermodynamic Properties

USING THE FORMAL thermodynamics developed above, the surface properties of a number of types of systems are investigated. The study of solutions of non-surfactant, non-electrolyte solutes is based primarily on the monolayer model. Equating chemical potentials of all components between the surface monolayer and the bulk phase leads to the set of Butler equations:

$$\sigma = \sigma_i + \frac{RT}{a_i} \ln \frac{\gamma_i^\sigma X_i^\sigma}{\gamma_i X_i}$$

where σ is the surface tension of the solution, σ_i that of pure component i , a_i the molar area of i in the surface, and $V_i^\sigma X_i^\sigma$ and $\gamma_i X_i$ the activities of component i in the surface and substrate, respectively. Ideal, regular, athermal, and associated solution models are used in both the bulk solution and surface monolayer to predict surface tension and surface composition of the solutions. Solutions of inorganic electrolytes are treated next, with emphasis on the modifications that must be made in the Gibbs equation for treatment of electrolyte systems. Solutions of surfactants are treated in detail, with special attention given to the phenomena of micellization and solubilization. Insoluble monolayers are treated

The diversity of problems in the realm of interfacial phenomena is staggering . . . the pitfall to avoid is the presentation of a parade of examples with insufficient attention to the common ground between them.

next, with emphasis on the two-dimensional phase behavior they exhibit. In the context of the discussion of insoluble monolayers, wetting and spreading phenomena are discussed in some detail, and a general phase rule for capillary systems is developed.

IV. Capillary Dynamics

THE UNIT ON "capillary dynamics" concerns surface tension driven (or surface tension influenced) fluid flow. Interfacial effects enter the problem via the boundary conditions, producing discontinuities in both the normal and tangential stress balances at the fluid interface. The normal stress discontinuity is proportional to the surface curvature, as given by the Young-Laplace equation: $2\sigma(T,X)\kappa_m$, while the tangential stress discontinuity is equal to the lateral variation of the surface tension: $\text{grad}_s\sigma(T,x)$, where grad_s refers to the surface gradient. Both force components may be appreciable in magnitude, and their evaluation requires knowledge of the surface tension dependence upon temperature and composition, i.e. thermodynamic information of the type studied in the foregoing work. When variations of surface tension are caused by variation in temperature and/or composition, the flow equations must be solved together with the thermal energy equation and/or diffusion equations.

When highly surface active solutes are present, $\text{grad}_s\sigma$ is proportional to the surface gradient of the surfactant adsorption, i.e. $(\partial\sigma/\partial\Gamma)\text{grad}_s\Gamma$. The surfactant distribution is given in turn by a surface material balance:

$$\frac{\partial\Gamma}{\partial t} + \text{div}_s(\Gamma v_s - D_s \text{grad}_s\Gamma) + j_n' + j_n'' = 0$$

where v_s is the surface velocity, D_s the surface diffusivity, and j_n' and j_n'' fluxes of surfactant from the adjoining bulk phases. The rate of interchange of material between interface and bulk may be governed by adsorption-desorption kinetics, molecular diffusion, or convective diffusion.

Finally, concentrated surfactant monolayers have been shown to possess intrinsic rheological properties, in particular surface viscosity. Terms involving the intrinsic surface rheological prop-

erties are incorporated into the tangential force boundary condition for such systems. Attention is focused on current studies, such as those in progress in our laboratory, of thermodynamic and transport properties of monolayers in multi-component systems and their application to flow problems.

A case study is made of the circulation within drops and bubbles moving through viscous media and the effects of temperature and composition variations upon such flows. A second case study of hydrodynamic analysis is made of "interfacial turbulence", and its effect on mass transfer.

LECTURE AND LABORATORY DEMONSTRATIONS

MUCH OF THE MATERIAL covered in this course lends itself to interesting and illuminating lecture or laboratory demonstration. C. V. Boys' monograph: "Soap Bubbles and the Forces which Mould Them" describes many possibilities. Suspending soap films on wire frames of various shapes to illustrate Plateau's problem (Determine the surface of minimum area passing through a given closed curve or set of curves in space) is a convincing illustration of a special case of the Young-Laplace equation. Advantage was taken of on-going research projects among the author's graduate students to provide laboratory demonstrations of the capillary rise and contracting circular jet methods for measuring static and dynamic surface tensions, respectively, as well as the Langmuir film balance technique for studying insoluble monolayers. Schlieren optics were used to display surface tension driven flows during mass transfer, and the excellent film by L. Trefethen "Surface Tension in Fluid Mechanics," Educ. Services, Inc. (1964) was used to illustrate numerous capillary phenomena.

CONCLUSION

The interest in this course shown by the graduate students in Chemical Engineering at Washington has been truly gratifying. Almost all of them either take or audit the class, and many express interest in taking topical courses which are extensions of material covered in this course. What is perhaps most gratifying of all is the wealth of constructive criticism and helpful suggestions these students provide.

A Course in

KINETICS OF CHEMICAL PROCESSES

M. BOUDART

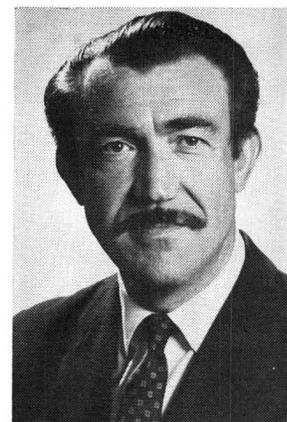
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THE RATE OF CHEMICAL processes can be studied at four different levels. In practice, the chemistry of the process is most frequently disguised under transport phenomena. The study of the interaction between physical and chemical variables in the chemical reactor is the province of chemical engineering kinetics or chemical reaction engineering. This discipline emerged in the late thirties and blossomed up after the war. It is normally taught to chemical engineers at both undergraduate and graduate levels.

The success of this first approach, especially in the design of reactors, depends largely on knowledge that is obtained at subsequent levels dissection of the chemical processes. A second level of knowledge is that of the process unfettered from gradients of temperature and concentrations. Usually the process then consists of a network of single reactions in parallel and in series. To understand the network, it is necessary to understand its component single reactions and the kinetic study of single reactions constitutes the third level of endeavor.

Indeed, each single reaction takes place normally through a sequence of elementary steps and the dissection of the single reaction into its component steps is a formidable task in the study of all catalytic and chain reactions.

Finally, kinetic information on the isolated elementary steps themselves must be obtained for a complete knowledge of the entire process. The study of elementary steps is the domain of pure chemical kinetics dominated by the theory of the transition state or activated complex. However, with the rapid development of molecular beams and computational techniques, the classical aspects of chemical kinetics are replaced more and more by a complete description which is the object of the new molecular dynamics. Both classical chemical kinetics and molecular dynamics constitute the fourth and ultimate level of kinetic knowledge and these topics are normally taught in advanced physical chemistry courses.



CLEARLY THEN, there is a gap between the first and the fourth levels of kinetic knowledge that must be filled, especially for the education of chemical engineers. This gap I have attempted to fill by means of a textbook published in 1968 by Prentice Hall. This book can be followed closely in undergraduate courses. At the graduate level, it can be supplemented by reading assignments from the current literature in *Journal of Catalysis*, *Transactions of the Faraday Society* and *Kinetics and Catalysis*.

The purpose of the course is to provide the student with the judgment required to obtain, evaluate and improve rate equations that must be used in the design, operation and optimization of chemical reactors. With a proposed rate equation, the important question is not so much: "how well does it fit the data?" but rather: "what does it mean physically?"

To answer the latter question, it is necessary to scrutinize the numerical values of the parameters of the rate equation. Of even greater importance than activation energies and enthalpies of individual steps, are standard entropies of activation and reaction. The advanced student must become able to pass judgment on possible rate equations from such a physical standpoint. He must recognize the frailty of numerical analysis in deciding between alternative mechanisms. He must free himself from routine application of a limited number of types of sequences of elementary steps. A lot can be done in this field with a bare minimum of chemistry.

The general tools available to the student who wishes to gain confidence in kinetics rather than become an expert are few, but they are powerful if they are well understood. They are: the theory of the transition state, the steady state approximation, the concept of rate determining step, the

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concept of most abundant intermediate and the idea of interaction between single reactions in parallel or in series.

Transition state theory remains the workhorse of pure chemical kinetics in spite of the exciting but limited forays at the new frontier of molecular dynamics. The important realization here is first that calculations of activation energies are ruled out for some time to come but that very simple and reliable estimates of entropies of activation can be made for many elementary steps. Theory does not provide numbers that can be used for design. These numbers must, alas, always come from the experimental reactor. But theory provides a useful guide that permits us to accept or reject possible rate equations.

The steady state approximation is the second general tool and it is so good as a rule that the further qualifications of "quasi" as in quasi steady state approximation seems to be unnecessarily cautious. Nevertheless, interesting exceptions are known and their discussion in a graduate course is apt to stimulate the more mathematically gifted student.

OF GREAT VALUE but much more limited applicability is the concept of rate determining step. While this concept is not foreign to the chemical engineering student, it is usually mis-

understood and it is of great importance to stress its meaning. Thus, it may come as a surprise to some students that it is still perfectly legitimate to talk about a rate determining step of a single reaction that has reached chemical equilibrium. Possible methods to assign a rate determining step are among the topics that are of interest to the more serious graduate students.

Another key idea which I have found particularly useful in the kinetic treatment of chain and catalytic reactions, is that of the most abundant intermediate. It is found frequently that among all the free radicals or adsorbed intermediates that take part in the sequence of steps, only one is "kinetically significant" because of its much larger concentration. Ways to predict such a situation and to take advantage of it, deserve proper attention and provide many useful illustrations.

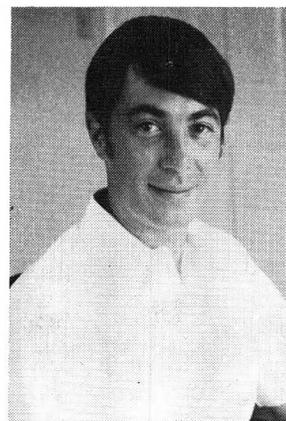
FINALLY, WHENEVER a reaction network must be treated, it is essential to keep in mind that the rates of single reactions in the network may be different from the rates of these same reactions measured individually. This is due to the interaction between single reactions as a result of competition of reactants for the intermediates appearing in the various sequences. Many fascinating cases of such interactions are known among chain and catalytic reactions. With mixed feeds, as for instance in steam cracking, these effects can be very striking.

Besides these five key concepts, a graduate course in chemical kinetics for chemical engineers should also cover the following topics: branched chain reactions, nucleation and growth especially in reactions involving solids, wall effects, proper measurement of catalytic rates, the principle of microscopic reversibility, thermal ignition, inhibition and the kinetic use of tracers. All of these are likely to be encountered by the chemical engineer engaged in process research and development. If the student becomes imbued with the power and generality of these kinetic principles, a course in the Kinetics of Chemical Processes can be very rewarding. Indeed, I feel rather strongly that a course of this type is a bread and butter course for all graduate students of chemical engineering. It has been my experience over the past nine years, first at Berkeley where I originated it and then at Stanford, that the material is well received even by students who have little affinity for chemistry.

PROCESS CONTROL

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GRADUATE LEVEL EDUCATION in process control poses several challenging questions to chemical engineering educators: What are its objectives? Which topics are of primary importance? To what extent is duplication of subject matter, with that of courses offered in electrical engineering, mechanical engineering, engineering science, etc., desirable and/or justifiable? How much duplication can be afforded with courses in optimization offered in our own departments? Should a single course be a "survey" and appeal to all chemical engineering graduate students, or should it be primarily directed at those who plan to do their thesis research in process control? What can be done to compensate for the enormous differences, in undergraduate preparation in process control, observed among students coming from various schools? Should laboratory work be included? What is a good balance between theory and applications?

Clearly, these questions occur in designing curricula for any area. However, the answers would appear to be less well-established for process control than for other areas of chemical engineering, perhaps because this is a relatively new subject. My purpose is to discuss graduate education in process control at Purdue, and how we have attempted to answer these questions.

SEVERAL FACTORS existing at Purdue may give us somewhat more than the usual amount of flexibility for experimentation in graduate education in general, and in graduate courses on process control, in particular. Our department has a relatively large number of graduate students, thus more nearly ensuring sufficient registration to offer a specialized course such as process control course each year. As a result, the course has been taught six times in the past seven years. There are three faculty members in the chemical engineering department interested in teaching a graduate process control course: Henry C. Lim, William A. Weigand, and

the author. Therefore, the course can be offered frequently without unduly restricting the teaching interests of any one faculty member. The average number of resident graduate students performing research in process control or related areas has exceeded ten over the past few years. This leads to a strong research interest on the part of students enrolled in the process control course. Purdue's departments of mechanical engineering, electrical engineering, engineering science, and mathematics offer several courses in control and closely related areas (such as systems engineering, mathematical programming, optimization, etc.). On the one hand, this relieves us of the pressure to cover a wide variety of topics, but on the other hand, increases our responsibility to avoid duplication by being aware of course content in other departments. The Purdue Laboratory for Applied Industrial Control (PLAIC), directed by Theodore J. Williams, supports graduate students from several departments, including chemical engineering, on industrially-oriented projects. Purdue graduate students interested in practical aspects of process control thus have opportunities for training in addition to those offered by the chemical engineering department.

A GAINST THIS background, our department has taught a 3-semester hour, graduate-level course, Advanced Process Control, hereafter referred to by its number, CHE 656. Over the several years it has been offered, some 35-40 graduate students have been enrolled in CHE

. . . familiarity with the current literature
is a primary objective . . .

656. Of course, there has been evolution in the subject matter, so that not all these students have studied the same material. However, all these students have studied material significantly more advanced than that covered in undergraduate process control courses. Since many other departments of chemical engineering are actively involved in graduate education in process control, it seems conservative to estimate that there are more than two hundred engineers now in industry who have had graduate training in process control or closely related areas. Therefore, it is not unreasonable to expect that these former graduate students should have had some impact on current process control technology. I wish to more closely examine this question later. To begin the discussion, I now return to the questions posed at the beginning of the article.

OBJECTIVES OF GRADUATE LEVEL EDUCATION IN PROCESS CONTROL

Many worthwhile objectives exist; listed here are those I believe to have highest priority.

The technology of *process operation* has become more complex, and is rapidly increasing in complexity. Use of the digital computer in plant operation is increasing. Plant optimization studies are conducted and result in changes in mode of operation as well as in operating conditions. Thus, I believe we should broaden the scope of the process control topic by calling it *process operation*. This subject has equal economic significance with its counterpart in classical chemical engineering — process design. One discipline attempts to optimize the plant before it is built, i.e., while it is on paper, and the other continues the attempt when the plant is operated. The typical undergraduate chemical engineering curriculum has room for only one course each in process design and process operation (control). There simply is more of practical value to learn about these subjects than can be studied in one undergraduate course.

The language of communication in process operation tends to be mathematical and therefore difficult. This fact generates two purposes for graduate-level courses — education of the students in the mathematical foundations, and simplification of the language (i.e., communica-

tion of the same information in simpler terms). Since we have inherited much of the foundations from mathematicians, this simplification aspect is potentially a valuable contribution of the engineer, both educationally and industrially.

The research and development literature on the automatic control and optimization aspects of process operation is widely scattered in a variety of journals, many of which are virtually unknown to chemical engineering students. As in most subjects in the graduate curriculum, familiarity with the current literature is a primary objective; in this subject, it is perhaps even more critical.

To summarize, key objectives of a graduate course on process operation are mastery of practically important subject matter which cannot be included in the undergraduate curriculum, mastery and simplification of the mathematical language, and familiarity with the literature. Granted these objectives are important in any graduate course; I have tried to show why they have high priority in process operation.

TOPICS COVERED

Since there are three faculty members who have taught the course, topics fluctuate slightly from year to year. Presented here is a summary of the topics included when the course is taught by me. The central textbook is reference (1). Supplementary sources in the bibliography are referenced by number in the discussion. In addition, numerous other literature articles are discussed.

Application of the digital computer to process operation: Owing to the growing number of chemical and petroleum plants being operated wholly or partially through a digital computer, I believe this subject must receive careful attention. Key topics are:

- (1) Basic theory of sampled-data control systems, including z-transforms, sampling theorem, closed-loop analysis, etc.²
- (2) Selection of sampling rate for typical processes.^{2, 3}
- (3) Design of digital control algorithms.^{2, 3, 4}
- (4) Smoothing and differentiation of computer-sampled signals.⁵
- (5) Applications of the computer to process control; direct vs supervisory control, optimization, data reduction and analysis.^{6, 5}

. . . key objectives . . . are mastery of practically important subject matter . . . , and mastery and simplification of the mathematical language

Optimal control: This subject has been the object of some controversy, based on the thesis that research in the area has advanced well beyond proven applications. Arguments for this thesis have been well-presented. Later in the article, I will state some of the counter-arguments which have led to the decision to emphasize optimal control in our graduate course. Topics are:

- (1) State variables for continuous and discrete systems; comparison of state variable approaches with classical input-output approaches.^{7, 8}
- (2) The minimum principle; optimal controllers for various processes designed by this principle, limitations, discussion of frequently occurring misconceptions on theoretical aspects, applications of results to practical situations, numerical methods.^{9, 10, 11, 12, 13}
- (3) Dynamic programming; same subjects as discussed for minimum principle, with comparison of the two approaches.¹⁴

Stability theory: Here again, considerable disagreement exists regarding the applicability of existing research results on stability to process control situations. However, there is no argument with the assertion that stability has been the central theme for development of most classical control techniques whose applicability is now unchallenged. It is likely that a majority of process control loops are tuned on the basis of degree of approach to instability. This is true despite the fact that instrument engineers do not in general make daily use of the classical theoretical stability concepts, such as the Routh-Hurwitz or Nyquist criteria. However, it is only through an understanding of these theoretical concepts that we can assert with confidence that control loops tuned in this manner will generally be reasonably close to "optimal" performance. Furthermore, understanding the theory guides us in the exceptional cases when these loop-tuning methods fail (e.g., the process does not exhibit sufficient phase lag) and avoids loss of confidence in the methods. These considerations are much more difficult to present concretely for more recent theoretical stability concepts, such as Ly-

apunov methods, but this is because we cannot yet use hindsight. An important contribution of our academic courses, in my opinion, is to emphasize similarly practical offshoots from modern stability theory. Thus, just as loop-tuning is an offshoot from the Nyquist criterion, highly sophisticated yet very practical on-off controllers can be designed on the basis of an offshoot of Lyapunov's methods. Topics are:

- (1) Definitions of various types of stability.^{6, 7}
- (2) Stability methods for linear vs non-linear systems.^{6, 7}
- (3) Lyapunov's methods.^{6, 7, 10}
- (4) Relations between Lyapunov's methods and the design and tuning of control loops.^{7, 1}

These three topics — digital control, optimal control, and stability—are the central themes of CHE 656. Clearly, these topics overlap; for example, optimal control of discrete systems will most likely be realized by a digital computer. However, the three topics do give the appearance of separate theoretical branches to the student, and we have chosen to treat them in this manner while mentioning interrelations at the appropriate points.

It is also evident that several important topics have been omitted from CHE 656, such as statistically designed control systems, and adaptive control. The time available in a one-semester course, which meets for a total of 45 lecture hours, is barely sufficient to give adequate treatment to the three selected topics. This selection is based purely on my own judgment of relative importance to the student's education. Undoubtedly, strong arguments can be made for alternative judgments.

DUPLICATION WITH OTHER COURSES

This potential difficulty has been less important than was anticipated when we first planned a graduate-level control course. CHE 656 actually has helped us take more advantage of systems engineering and automatic control courses offered in other departments. The preliminary study of automatic control in CHE 656, with a view toward process application, better

**We . . . have attempted to teach a course
that can appeal to all graduate students . . .**

prepares students to absorb the somewhat more mathematical and abstract treatment in courses taught in other departments, which delve more deeply into the subject matter.

More difficult is the problem of duplication with chemical engineering graduate courses on optimization, particularly on the subjects of dynamic programming and the minimum principle. We have not yet taught a graduate course in optimization at Purdue, so have not really faced the problem. However, it is not difficult to anticipate that where both are taught, close communication between these two courses is important.

OTHER CONSIDERATIONS

We have decided not to direct CHE 656 primarily to those students doing research in process control, but rather have attempted to teach a course that can appeal to all graduate students. I am convinced that the subject of process operation is important to all chemical engineers and further that the mathematical facility gained from its study is useful to Ph.D. students specializing in all aspects of chemical engineering.

The undergraduate preparation of students from different schools, in process control and related aspects of mathematics, varies drastically. This problem, which seems to affect graduate level process control courses at least as much as any other graduate courses, is one I have only learned to live with. Some relief can be obtained by using time-domain approaches over frequency-domain approaches whenever possible. Frequent examples of small dimension (i.e., 2×2) can (very gradually) infuse the student, having virtually no background in algebra, with some confidence in interpreting vector-matrix equations. Other similar measures can be devised.

Some students have little, if any, undergraduate laboratory experience in process control. In such cases, we urge that the graduate student audit the laboratory section of our undergraduate control course.

THEORY VS APPLICATION

Several years ago, at a meeting of process control computer users and vendors, I presented a paper pointing out that sampling the output of

a process approximately 4 times per time constant is a breakeven point for process control. In other words, once the sampling rate is this fast, closed-loop performance cannot be significantly improved simply by increasing the sampling rate. This fact has been well-established in theory and in most automatic control applications, with the exception of process control. Instead of this, process control computer users and vendors were attempting to establish industry-wide standards calling for sampling frequencies at once per second for flow loops, once per 5 seconds for pressure loops, and once per 20 seconds for temperature loops, *regardless of process response time*. My remarks elicited considerable discussion, particularly from vendors who already had considerable investment in hardware and software based on the faster sampling rates. Three years later, a former Purdue graduate student telephoned. He was specializing in computer applications for a manufacturing company, one of whose personnel had attended this earlier meeting. Together they had conducted a project to study the use of slower sampling rates. The problem was this: A digitally controlled loop, previously sampled at a frequency of once per 20 seconds, showed a closed-loop oscillation with a period of approximately $\frac{1}{2}$ hour. This indicates a process time constant of the order of 10 minutes. Therefore, according to theory, it should be possible to reduce the sampling to once every 150 seconds without significant degradation of performance. However, when only every eighth measurement was used to decide on a new control valve position (i.e., when the sampling frequency was lowered to once every 160 seconds), the loop performance was much slower and more oscillatory than before. They very kindly invited me to visit the installation, which I did. The difficulty turned out to be this: Exponential smoothing with a constant value $\alpha = 0.3$ was being used to filter noise in the sampled values of the process output. (In exponential smoothing, the smoothed measurement is taken as α times the current raw measurement plus $(1 - \alpha)$ times the previous smoothed measurement.) This smoothing procedure is very similar to using an ordinary continuous filter and the equivalent R-C time constant can be approximately calculated from the values of α and the sampling rate. In the original loop, the filter time constant thus estimated is 1 minute, very reasonable for the 10

(Continued on page 203)

A Course in

BIOENGINEERING

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New York, New York

IF BIOENGINEERING as an area of technical endeavor were to fulfill its many hopeful definitions; if the recognized problems of medical practice and biological research were to have all the help which it is now apparent that engineering could give them; if the human organism were to receive so much analysis relative to its complexity as it is now customary to assign to a new chemical process; if the delivery of health care were to be planned with so much care as is now used to optimize a distribution network for petroleum products; if, in short, there were to be demanded by the sprawling enterprise which man has built to study, strengthen and maintain himself only so much engineering effort as has been shown to be beneficial in more circumscribed endeavors, the requisite expansion of the profession of engineering would consume all its resources for many years to come. In fact, such a demand is unlikely.

Casting aside momentary concerns caused by retrenchments in the domestic budget of the United States, it is apparent even to the casual student of the sociology and history of science that there are more long-lived impediments. An intellectual divergence, began more than a century ago, has led to separate scientific conglomerates in the physical sciences (including engineering) and the biological sciences, the former based on presumptively determinate, precise, physical models usually as much formulated to suit the analytical tools available as to conform to the reality of interest, and the latter on necessarily indeterminate, qualitative, fractionally analyzable, biological systems, studied as found because they lost their nature when reduced in complexity. Admission to these circles has demanded commitment either to precision or to reality: in biology one might study a model but the ultimate test lay not in the consistency of the model's behavior but in its relevance to the living system it was made to represent; in physi-

cal science one might speculate about the utility of a model but peer judgment has largely centered about how completely it was analyzed and how internally consistent it was. The stunted growth of biophysics testified clearly to the difficulty of rejoining the goals of perfection in the abstract with relevance to life as lived.

THUS TWO MAJOR obstacles impede the introduction of engineering technology into medicine and biological science: the persistent complexity of analyzing living systems and the largely unreconciled standards of the peer groups in the biological and physical sciences. It is safe to predict that one or two generations of discovery and sociological accommodation will pass before engineering will, explicitly or implicitly, occupy an optimal role in the development and application of biological knowledge. Yet it is also safe to anticipate a happier future for bioengineering than for biophysics because the timeless role of engineering has been the reconciliation of abstract science with realities, those of nature and those created by the mind and hands of man.

Two steady trends create favorable circumstances for the development of bioengineering: pressure to use rapidly accumulating knowledge about parts of organisms which has not yet been fully exploited to predict the normal and disturbed performance of intact living systems, and the shift within all engineering to a stronger interplay between analysis and synthesis.

NOTWITHSTANDING such favorable omens, the challenge of passing optimally from the present flirtation to the future union is large. The interaction of engineering, including its many specialties, with the many biological disciplines is far too broad to serve as a focus of activity for the individual or a working group.

Classically, the specialties of engineering have proliferated by the interaction of an established discipline with an important, new area of application. A new discipline evolved when the interaction spawned concepts and techniques primarily useful in the area of application but of broad value in other areas of concern to engineers, when the transmission of these concepts to a new generation required new courses, when special subjects and the basic sciences on which they depended became central in the curriculum. How else was chemical engineering born but by the prolonged interaction of mechanical engineers with the chemical industry? Straightforward

. . . If there were to be demanded by the sprawling enterprise which man has built to study, strengthen and maintain himself . . . the requisite expansion of the profession of engineering would consume all its resources for many years to come . . .

repetition of this pattern in the present instance appears impossible. The volume of information necessary to represent the field of application is enormous; the sciences and areas of engineering technology which are demonstrably useful encompass several curricula most of which are themselves near the bursting point. A 'bioengineer' educated to apply all parts of engineering to all parts of biology might be called upon to:

- make a kinematic analysis of the indeterminate structure represented by the bones and muscles of the skeleton.
- determine optimal positions and time schedules for administering drugs to specified target organs, minimizing dosage to other capillary beds.
- apply lubrication theory to the analysis of normal and diseased joints.
- design artificial organ systems based on membrane transport processes and enzyme reactions.
- determine if certain reactions occurring in the bloodstream were kinetically or diffusionally controlled.
- study damage to blood passed through artificial pumps, conduits, and exchange devices.
- evolve a systems model of all or part of the body's neuromuscular structures.
- find a quantitative relationship between electrical potentials on the skin surface and electromechanical events in cardiac muscle.
- determine the shape of normal and diseased erythrocytes passing through capillaries smaller than their major diameter.
- relate piezoelectric potentials to bone growth.
- study and model long-term effects of a weightless environment on gastrointestinal motility.
- devise radiotracer experiments to localize in space and on the reaction coordinate derangements of normal metabolic reactions.

Consideration of the nature of these and many other tasks which have also been actually undertaken, as well as the scope of activity which they define, suggests that the interaction of engineering with the biological establishment can hardly avoid evolving as specializations between each of the major engineering disciplines now existing and appropriate clinical and scientific specialties in medicine and biology. No single discipline is broad enough to support bioengineering in the forms which have already developed and no single new discipline seems capable of encompassing the useful content of existing disciplines. Rather, at a time when the ex-

tant disciplines are becoming less clearly identified with a particular area of application and more clearly with concepts, sciences, and techniques, and in the absence of widely recognized, performed conceptual innovations in the area of application, bioengineering seems destined to develop as a collection of subspecializations, each potentially a major component of the parent discipline.

Bioengineering, as considered here, is primarily concerned with understanding, diagnosing, maintaining and augmenting the human organism. Chemical engineers have been and will be concerned with other biological endeavors: chemical processing with organisms and enzymes and processing of materials of plant and animal origin (often called 'biochemical engineering') and study of interactions among organisms and their surroundings (the analytical endeavor being called 'ecology' and the synthetic effort 'environmental engineering'). In each of these areas the biological information necessary for immediately (but not necessarily ultimately) effective action is more accessible and the activity is thus more technological and more closely related to classical engineering. In these areas control of the application of the engineering endeavor rests with the engineer and industrial managers. **In very large part the special educational and professional problem of the bioengineering considered here is the need for the engineer to become newly and deeply involved in biological science, even to the point of helping to restructure it, and deeply involved in applications**

As this manuscript was being completed, the author learned of the sudden death of Erwin H. Amick, professor and chemical engineering department chairman at Columbia. His encouragement was instrumental in some of the earliest as well as latest involvements of chemical engineering with bio-engineering at Columbia. His premature loss is mute testimony to what remains to be discovered that more of humanity might enjoy a full span of useful life. With sorrow and respect this article is dedicated to his memory.

Since 1969, Edward F. Leonard has been Professor of Chemical Engineering and director of the Artificial Organs Research Laboratory at Columbia University. He received his B.S. degree from Massachusetts Institute of Technology and his M.S. and Ph.D. degrees from the University of Pennsylvania. He has served as an organizer of the Bioengineering Division of AIChE, as Chairman of the AIChE subcommittee on Engineering Fundamentals in the Life Sciences, and as Vice-chairman of the United States National Committee on Engineering in Medicine and Biology. At Columbia, where he has been on the faculty since 1952, he has been chairman of the committee on Bioengineering. He has devoted a large part of his research to a study of transport processes, particularly as related to the artificial kidney for which he has designed test cells for the evaluation of membrane permeabilities, studied blood flow, and worked on designs of artificial kidney devices. He is the author of numerous papers in this field and has presented several AIChE Today Series on this subject. He has served as consultant for St. Luke's Hospital and lecturer at the Mt. Sinai School of Medicine.

of his effort which have classically been reserved to another profession — medicine.

THAT CHEMICAL ENGINEERING should father such a subdiscipline seems indisputable. The analogy between inanimate chemical processes and metabolism is widely recognized. Prototype studies by chemical engineers show the roles of homogeneous and heterogeneous kinetics, the effects of convection and diffusion on rates and yields in living systems, and the utility of both elementary and complex analyses based on stoichiometry, thermodynamics, and momentum, energy and mass transport. Chemical engineers have collaborated with physiologists, anatomists and biochemists as well as those in such clinical disciplines as pathology, internal medicine, surgery, pediatrics, orthopedics, and urology. These collaborations have addressed problems in basic research where methods well-known to chemical engineers have defined innovations in clinical

research, permitting new approaches to the analysis of data and to the design of subsequent experiments; in therapeutic medicine, where dosage schedules and programs for the use of mechanical respirators have been fixed by engineering analysis; in diagnostic medicine, where more sophisticated processing of data has yielded a sharper identification of pathological states; and in artificial organ therapy, where engineered devices, in part prescribed and controlled by engineering criteria, have replaced natural organs, first only in acute but now also in chronic situations. (No tone of triumph should emanate from such a citation. Few of these accomplishments were the first of their kind. Some attempts have led to scientific failure or, worse, to clinical disaster clearly attributable to wrong or incomplete engineering analysis. In several cases engineering studies have been more successful in clarifying or extending concepts of general utility in engineering than in solving the biological problem, the new insight being contributed as much by the biological collaborator.)

In essentially all such studies the chemical engineer has either collaborated with a biological scientist or has previously had several years of such collaborative experience. The experience of these studies is sufficient to indicate the important ways in which chemical engineers will practice bioengineering in the years immediately ahead and the extent and kind of training which they will need. The balance of this paper details such an interpretation.

Serious involvement in bioengineering requires a reasonably complete knowledge of the elements of certain biological sciences: biochemistry, anatomy, cell and mammalian physiology. For most courses in biochemistry and physiology, organic and physical chemistry are respective prerequisites and both prerequisites are helpful for either biological science. Thus the chemical engineer is uniquely well prepared among engineers for the assimilation of the biological sciences mandatory for bioengineering.

MANY BIOCHEMISTRY departments offer a broad but rigorous graduate course for non-biochemists with content, but not necessarily emphasis, equivalent to what is offered to medical students. Such courses are not more poorly organized for the use of bioengineers than are typical courses in organic chemistry for chemical engineers. At Columbia University most chem-

ical engineers with a major interest in bioengineering take the first semester of a two-semester biochemistry sequence; many continue into the second semester which concentrates on intermediary metabolism.

Anatomy as taught to medical students is overly long and detailed and fails to emphasize principles. Nonetheless, bioengineers can profit greatly from the study of anatomy. Needed, if at all possible prior to the study of physiology, are one skill and one area of understanding. The skill is the ability to recognize and separate biological structures such as nerves, muscles, bone, cartilage, arteries and veins, and the principles (as well as the few principal exceptions) which determine how these elements are juxtaposed. To acquire this skill some non-vicarious manipulative experience is necessary. The understanding is of functional anatomy: the why of anatomical structure and the response of living tissue to mechanical stimulation. At Columbia a good course offering 3 points of credit in each of two semesters is available; different parts of the body are considered in each semester. Normally one semester is taken, preferably that dealing with the torso.

Cell physiology is often self-taught as bridging material between biochemistry and mammalian physiology. Both related subjects are much better appreciated, especially for the chemical engineer, if a course in cell physiology based on reasonable amounts of physical chemistry is taken after the study of biochemistry and before physiology.

At opposite ends of this recommended chronology of study in biological science are courses in basic biology and mammalian physiology. In many universities the former presume no knowledge of quantitative chemical and physical concepts and are thus highly descriptive, compendious, and low in conceptual content. What is needed is a course in which fundamental concepts of biology are succinctly introduced with concise, not exhaustive, illustration. The concepts should include the basic metabolism of plant and animal cells; the metabolism of the single-celled organism and its environmental interactions; the phyla of multicelled organisms, their metabolism, their evolutionary position, and their rationale in terms of environmental interactions; and an introduction to the study of genetics, growth and development. Ideally such a course should bridge between engineering and

No single discipline is broad enough to support bioengineering . . . and no single new discipline seems capable of encompassing the useful content of existing disciplines.

biological terminology wherever possible (example: showing explicitly the increase in importance of convective transport as one considers larger, more complex organisms). Practically, a clear, precise, noncompendious course in biological concepts would alone be a large enough innovation on most campuses not to be risked by insisting on a bioengineering flavor. An appropriate introductory course is a recent innovation at Columbia. Previously, decisions about how to begin a sequence of study in biological science were made individually. Students who felt sufficiently secure even if only on the basis of a high-school course in biology or some summer reading were encouraged to start with biochemistry accompanied or followed by cell physiology.

THE CLIMAX of a bioengineer's exposure to contemporary biological science should be a full course in human physiology such as that given to medical students, and including the laboratory. Physiology integrates all other biological sciences and as much physical science as has been made operational in biology into an integrated view of the normal human organism. It also deals cursorily with pathological states and pharmacological interventions. Even with the preparation indicated above, engineers can find such a course to be difficult. The usual, detailed treatment of neurophysiology uses the nomenclature of neuroanatomy. The fact-to-concept ratio of physiology is large, reflecting the general state of biological science. 'Logical' explanations of neurohumoral mechanisms consist, in fact, of one of several possible explanations. The system under consideration is so complex that rare indeed is the instructor who can discuss alternate explanations and the reasons for finding most favor with one. These difficulties notwithstanding, medical physiology courses are the major sources of organized facts about human function and are not far removed from the state of the art with respect to the consideration of the human organism as a system. At Columbia the course is most easily available in the summer session, five and one-half full days per week for six weeks, for which nine semester credits are given. In the laboratory classical experiments

(Continued on page 183)

A Course in

DESIGN OF AIR POLLUTION CONTROL SYSTEMS

WILLIAM LICHT
University of Cincinnati
Cincinnati, Ohio



THE COLLEGE OF ENGINEERING at the University of Cincinnati has a program in Environmental Health Engineering which is administered under the Department of Civil Engineering. A curriculum in air pollution control leading to M.S. and Ph.D. degrees, was established three years ago with the support of a training grant from the National Air Pollution Control Administration of the U. S. Department of Health, Education and Welfare. This grant also supports a concurrent program given in the Kettering Laboratory of the Department of Environmental Health of the College of Medicine.

The Engineering program is being presented by a team of three faculty members headed by Dr. John N. Pattison, Research Professor of Environmental Health Engineering. I was invited by Dr. Pattison to present the contributions which the discipline of chemical engineering can bring to bear on the solution of control problems. Third member of the team is Professor Charles W. Gruber who is a mechanical engineer and served for a number of years as the air pollution control officer of the City of Cincinnati.

Dr. Pattison's invitation was accepted enthusiastically for two principal reasons. First, because I have had a long-standing interest in particulate (fluid-solid) systems such as are involved in dust collection. But equally important, I have a firm conviction that chemical engineers have the best background of *any* discipline from which to tackle pollution control problems. There is a great challenge and opportunity for them to use their talents and training in this way. As an educator I feel a real responsibility to bring this to their attention and to provide encouragement, as well as the education, for them to consider a career in the environmental control field. I saw the new Air Pollution Control program as an excellent opportunity to do this.

AS A FIRST STEP in this direction, a senior level undergraduate elective course "Intro-

duction to Air Pollution Control" was developed at Cincinnati, and also given at Minnesota (as a Visiting Professor in Chemical Engineering) in 1968. This year over half of the 65 students enrolled in the course, now given by Professor Gruber, were chemical engineering seniors.

Dr. William Licht, a graduate of the University of Cincinnati, has been Professor of Chemical Engineering there since 1952. He also served as Head of the Department of Chemical and Metallurgical Engineering from 1952 to 1967. His industrial experience includes a period of employment with the Dow Chemical Company and various consulting assignments. The latter were especially related to work on the drying of refrigerants and gases, and recovery of dust by filtration. His technical publications and patents also disclose the results of research on the properties of azeotropic mixtures, development of dew-point indicators, adsorption in fixed beds, and transport phenomena involved with moving drops. In 1967 he became associated with the air pollution program in the Environmental Health Engineering activities of the College of Engineering, in which he is presently teaching Design of Air Pollution Control Systems. He is also serving as Vice-chairman of the Air Pollution Board of the City of Cincinnati.

The students in the graduate program, however, are welcomed with a rather wide variety of backgrounds in several branches of engineering, as well as in chemistry or physics. They also have a variety of career objectives. Some are aiming toward positions in government control agencies, others to industrial engineering work, and still others to the design and research of control methods. Consequently, the courses given, and the program for each student, must involve

. . . chemical engineers have the best background of any discipline from which to tackle pollution control problems. There is a great challenge and opportunity for them to use their talents and training in this way.

a high degree of flexibility and adaptability.

The principal graduate course which brings the chemical engineering approach into the program is called "Design of Air Pollution Control Systems". It is offered as a second level graduate course following prerequisite courses in Small Particle Technology and in Air Pollution Control Methods. Chemical engineers however usually can enter the course without these formal prerequisites. They find it relatively easy to pick up the necessary material because of the nature of their general background.

Small Particle Technology is essentially a treatment of particle-fluid mechanics. It deals with the motion of aerosol particles under the influence of various forces such as gravitational, inertial, centrifugal, electro-static, diffusional thermophoretic, photophoretic, etc. In particular, motion is studied in the neighborhood of surfaces of various shapes: plane, cylindrical, and spherical. Methods of measuring particle size, and describing size distribution in particulate mixtures are also studied. The text has been Fuchs' "Mechanics of Aerosols" (Macmillan, 1964). Davies' "Aerosol Science" (Academic Press, 1966) is also an appropriate source of material.

AIR POLLUTION CONTROL METHODS is a survey of the various devices available for the collection of particulate matter (cyclones, scrubbers, electrostatic precipitators, filters, etc.) and processes for the collection of gases (absorption, adsorption), or for gas and odor removal by combustion. The principles involved in the operation and successful application of the devices are discussed qualitatively, and from a practical industrial point of view. Field trips and methods of measuring source emission are also included. The reference text is "Air Pollution Engineering Manual" from the U. S. Public Health Service.

With a background equivalent to these two courses assumed, the course in Design presents the mathematical modelling of the collection devices and systems. It is presently given in a two-quarter sequence of three (quarter) credits each i.e. a total of about 60 lectures. However, since it has so far been presented only twice it is still in a state of development. Future plans

contemplate expansion of this course to three quarters.

The first quarter begins with a comprehensive check-list of all the factors which might need to be taken into account in designing a control system to meet a given pollutant emission problem. This provides an outline and a motivation for the topics which follow.

We then take up the modelling of particulate collection devices. The objective of the models is twofold: to predict the efficiency of collection as a function of system parameters, and to predict the pressure drop, hence energy requirements for operation. The order of topics is arranged according to increasing complexity of the system of collecting forces involved, as follows:

Collection on surfaces

- Gravity settling chambers (gravitational)
- Electrostatic precipitators (electrostatic)
- Cyclones (centrifugal, and gravitational)

Aerodynamic capture

- General principles
- Filters (inertial, diffusional, electrostatic)
- Scrubbers (inertial, gravitational)

The "classical" models for most of these devices are rather unsophisticated and oversimplified. They tend to assume plug flow, for example, and to ignore boundary layer effects, as well as turbulence. They always assume that when the path of a particle is such as to bring it into collision with a surface it will be collected or captured on that surface.

It is not surprising to find that the degree to which the models succeed in representing actual performance is poor. Attempts are made to develop more sophisticated models by taking into account such concepts as turbulent mixing of dust in gas streams, velocity distributions, residence time distributions, and boundary layer behavior. These are all concepts drawn from various standard chemical engineering operations which seem to be transferable to the particulate collection problem. Research projects are under way in this connection.

THE SECOND QUARTER is largely devoted to the collection of gases and to the chemical aspects of emission control. Gaseous collection is considered first by a continuation of the study of scrubbers used as gas absorbers, and of gas absorption design in general. This is followed by

fixed-bed adsorption. Combustion calculations are then reviewed and extended to the complex systems encountered in stack or exhaust gases containing oxides of sulfur and oxides of nitrogen. The role of the thermodynamics and kinetics of the reactions involved in the formation of these pollutants is explored. Special effects relating to the psychrometry of these stack gases are also presented. Finally, we examine specific control methods which are now being developed for certain gases.

At various appropriate points in the course the basic concepts of system and equipment design optimization are introduced and applied to the air pollution control system. Generalizations relating to costs and economic aspects of control systems are likewise brought in. It would be desirable to give a more thorough treatment of these matters. This is one motivation for lengthening the course to three quarters. It would also be desirable to present computer simulation of control devices.

The method of instruction involves asking the students to solve a number of problems specially devised for the course. Some of these are numerical illustrations of the use of the models or design methods. Others, however, are open-ended design problems in which judgment and ingenuity may be exercised and alternative solutions considered. The effect of a particular system parameter is illustrated by having different

members of the class do the same calculation with each using a different value of the specified parameter, and then pooling the results into one overall picture.

There really is no text which is quite appropriate for this course as it is now conceived. The one used thus far has been "Industrial Gas Cleaning" by Strauss (Pergamon, 1966). Material has also been drawn from Stern's "Air Pollution", especially Vol. III of the 2nd edition (Academic Press, 1968). Much use is made also of original literature references. There is a lot of interest in these problems today, and new work is appearing with increasing frequency.

It is hoped that chemical engineering students will find increasing interest in dealing with air pollution problems, especially through the approach taken by such a course as this. Many of the concepts which are familiar to them in reactor design and in transport phenomena, can be transferred immediately with very fruitful results. Every effort is made to show them, and all students, that the pollution problem is not only serious enough to demand their attention as concerned citizens, but also challenging and sophisticated enough to captivate their intellectual interest at the highest level of professional competence. This applies not only to the present, but certainly even more so to the future developments in research and design.

ChE problems for teachers

Submitted by Professor R. M. Felder, North Carolina State University at Raleigh.

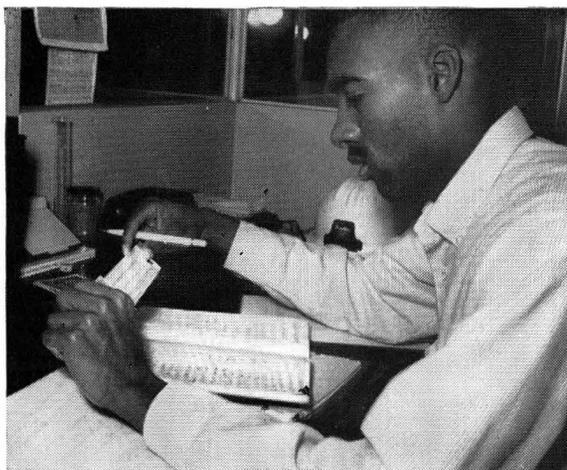
A graduate student in your seminar on existential reaction engineering bursts into your office, barely giving you time to cover Playboy with Chemical Engineering Progress, and announces that he has formulated a proof of man's nonexistence based on the known effects of diffusion in tubular reactors. All thoughts of the Playmate of the Month are forgotten as visions of publications, promotions, awards and enduring fame dance in your head. (You would, of course, acknowledge helpful discussions with the student in a footnote somewhere.) You casually express an interest, and the student promptly erases the irreplaceable notes on your blackboard and offers the following demonstration:

Consider a laminar flow tubular reactor in which a single first-order reaction occurs. Now

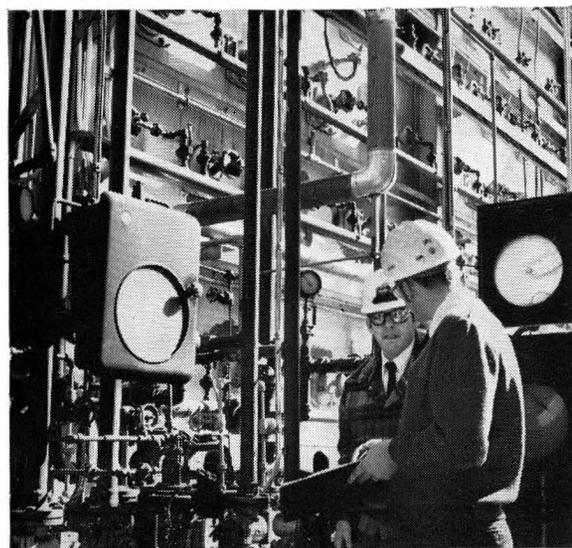
1. Radial diffusion brings the reactor closer to plug flow, and therefore increases conversion. On the other hand
2. Axial diffusion brings the reactor closer to a stirred tank, and therefore decreases conversion. But

3. Radial diffusion can be represented as axial diffusion using the Taylor model. Therefore
4. Radial diffusion both increases conversion [from (1)] and decreases conversion [from (2) and (3)]. The only way this can be the case, however, is if
5. Radial diffusion does not affect conversion at all. But we all know that it does, and consequently
6. Radial diffusion does not exist. Moreover, by applying a coordinate transformation which maps the radius onto the axis and vice versa, it can easily be shown that axial diffusion also does not exist. In short,
7. There is no such thing as diffusion in tubular reactors. But everyone knows there is, and therefore
8. Tubular reactors do not exist. But I am certain beyond all possible doubt that tubular reactors exist, which can only mean that
9. I do not exist. Q.E.D.

Sadly, you realize that you might just as well have kept your thoughts on Miss October, and that any enduring fame you get will have to come from your process to manufacture sand from glass (patent applied for). Meanwhile it's almost time for lunch, so you decide to ignore the student's philosophical fallacies and simply advise him where his engineering analysis [Steps 1-4] falls down. What do you tell him?



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Two Courses in

FLUID MECHANICS

A. B. METZNER and M. M. DENN

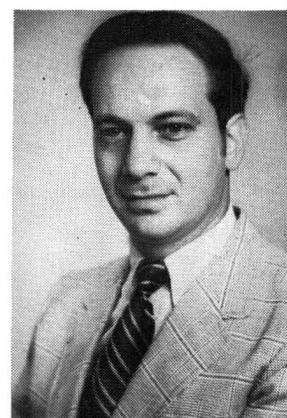
University of Delaware

Delaware, Maryland

FLUID MECHANICS plays a central role in many problems of interest to chemical engineers, yet it is only in recent years that courses have been developed which meet the unique requirements of the chemical engineer, as distinguished from the traditional aerodynamical orientation of the subject. For example, chemical engineers need to devote considerable attention to moderately slow flows of viscous materials, frequently in the laminar regime, and in many cases the problems are associated with the flow of complex materials with a memory for their deformation history. It is in recognition of needs such as these, taken together with the more traditional fundamentals of the subject, that we have developed our graduate courses.

The fluid mechanics program at the University of Delaware is typical in structure and philosophy of the way in which we do most of our graduate instruction. There are three levels of activity. The first course is designed partly to strengthen and supplement the student's undergraduate understanding of an area, and partly to develop more general and more powerful analytical tools. The course emphasizes material which is likely to be of design importance to the student, Masters or Ph.D., who goes into industry. We offer the basic fluid mechanics (and thermodynamics) course during the fall semester so that a firm foundation in fluid mechanics can be assumed and efficiently built upon in the basic heat and mass transfer and kinetics and reactor analysis courses offered in the spring.

The second level course, offered in the spring or summer in this subject, is provided for those students with a particular interest in fluid mechanics and proceeds to the frontiers of the area. This course is "team-taught" by four or five faculty, each emphasizing his own particular research specialty. In this course the distinction between student and instructor is no longer as great, and postdoctoral fellows may participate



A. B. Metzner received his B.Sc. degree at the University of Alberta and his Sc.D. at M.I.T. He has been at the University of Delaware since 1953, became chairman Feb., 1970. He has Research interests in transport phenomena, especially the mechanics of viscoelastic media. He has received Colburn award of A.I.Ch.E. (1958) and the Wilmington section award of the ACS, also in 1958. He was the first annual Chemical Engineering Lecturer of ASEE in 1963 and served as a Guggenheim Fellow at Cambridge in 1968-69. (Left)

M. M. Denn received his B.S.E. degree at Princeton University and his Ph.D. at Minnesota. He has been at the University of Delaware since 1964 and presently is Associate Professor of Chemical Engineering. He has research interests in viscoelastic fluid mechanics and optimization and control. He is the author of "Optimization by Variational Methods," McGraw-Hill, 1969, and co-author of forthcoming "Introduction to Chemical Engineering Analysis," Wiley, 1971. (Right)

in both roles, as do advanced graduate students. Finally, we have regular seminars which are primarily for the benefit of faculty and students with research interests in an area. In these the student-faculty role is, ideally, completely blurred. Such seminars are probably common to all good departments of chemical engineering and differ only in the specific subject areas of interest. (During each semester of the recent academic year we had two seminars in areas of fluid mechanics, one emphasizing two phase flows, the other viscoelastic fluid mechanics.) In the discussion which follows we shall emphasize only the two courses, which we believe have been quite successful and may be somewhat unique.

BASIC COURSE IN FLUID MECHANICS

ALL OF OUR graduate students are from other departments and bring to Delaware a variety of experiences in undergraduate in-

The first course emphasizes material of design importance and the second level course carries one to the frontiers of the subject.

struction. Though undergraduate courses in fluid mechanics have become increasingly rigorous in recent years, the new graduate students rarely have a firm fundamental understanding of the subject. This may be due in part to the continuing aerodynamics bias of many undergraduate courses in which, because interest is confined to Newtonian fluids, no clear distinction is made between *basic conservation principles* and *constitutive approximations*. As a result we find it efficient to start from the beginning and to develop the entire subject in an orderly manner which carefully distinguishes between rigorous principles and necessary, but often crude, approximations, and which emphasizes chemical engineering interests. Since the students are a select group it is possible to proceed rapidly with material which has been covered in part before and so any partial redundancy does not result in appreciable loss of time. The following course outline has been utilized for several years.

Our course begins with a consideration of the algebra and calculus of tensors. This represents the "natural" language when dealing with fluids exhibiting complex physical properties and is thus the doorway to much of chemical engineering fluid mechanics, as well as providing for an increased efficiency in the way in which classical material may be treated. The initial material is thus intended to serve as a foundation for all of non-linear continuum mechanics. The specific subjects covered include addition, subtraction, and multiplication of tensors; tests of tensor character; the metric and conjugate metric tensors; and the significance of tensorial and physical components of tensors. The Christoffel symbols are developed and differentiation of tensors is considered in some detail.

The notion of stress and the equations expressing the basic conservation principles, conservation of mass, momentum, and energy, are developed in a fixed Cartesian coordinate framework. Utilizing the algebra and calculus of tensors developed earlier, these equations are then efficiently transformed into other coordinate systems. A significant number of example problems are provided both at this point and previously to enable the student to develop competence and confidence in his ability to understand the

basic conservation principles and to derive them for any coordinate system of interest in a given problem.

Thirdly, constitutive approximations for purely viscous fluids are introduced. Since the thermostatic constitutive equations for fluid density and internal energy are the simplest to understand, these are considered first. Following a quantitative description of deformation rate and vorticity, the rheological constitutive equations for description of the stress-deformation rate relationships for purely viscous fluids are developed. Some simple constitutive approximations for the stress-deformation rate relations of viscoelastic liquids may be introduced as well. Finally, for purposes of completeness, though in fact little use is made of this in the first course, the constitutive equations for relating heat fluxes to the temperature field are also introduced and illustrated by means of a few example problems.

The above provides the student with a sound understanding of the difference between those equations which represent universally valid descriptions of conserved quantities and the perhaps crass and empirical nature of the constitutive equations introduced to describe the physical properties of particular materials. Unidirectional flow problems are now solved in large quantity. These enable the student to proceed by first applying the general relationships, in order to describe the problem as fully as possible without introducing empirical approximations, and then, when he has gone as far as he can on a perfectly general basis, to introduce the appropriate linear or nonlinear constitutive description necessary to provide enough information about the material being processed in order to obtain a solution to the required problem. These problems also serve to introduce the student to the methods of measuring pertinent physical properties of fluids. Incidentally, the student quickly learns through these simple flow problems that the usual way of solving problems in fluid mechanics is to anticipate the form of the answer in advance and then to construct the details of the solution by using the conservation principles and constitutive approximations. This sequence is implied in all treatises on fluid mechanics but rarely stated.

Simple flow problems are usually confined to laminar flows, and we next introduce the student to the simplifying approximations of Prandtl for flows which are nearly unidirectional

and in which the Reynolds number is large. This area of boundary layer theory is used to sharpen the abilities of the student to make simplifying approximations, rather than to solve a large number of problems of interest only to the aerodynamicist. The presentation in this part of the course is classical, except that the important pedagogical contributions of Acrivos are used in order to illustrate clearly the fact that one can obtain much information from the differential equations without solving them fully.

Finally, we deal with the nature of turbulent flow, its description by means of the Reynolds equations, and the approximate solutions to these obtained by individuals such as von Karman, Taylor, Prandtl and Milliken. This does not provide any insight into the more recent developments in turbulence theory but it does provide the student with essentially all of the information on turbulence which is of design value at the present time.

SECOND LEVEL COURSE IN FLUID MECHANICS

THE FIRST COURSE provides the student with the basic mathematical skills necessary for work in all areas of fluid mechanics and additionally provides him a substantial body of design information and an ability to develop this for himself when new problems are encountered. It has not, however, taken him to the forefront of current research activities in any of the areas enumerated. This is achieved in the second course by subdividing the total course into four or five sections, each of which is taught by an individual who is an active researcher in the specialty being considered. This "team teaching" requires a great deal of faculty time but it represents an extremely effective way of taking a substantial number of students to the frontiers of research in a variety of areas. The subjects covered vary

This "team teaching" . . . represents an . . . effective way of taking . . . students to the frontiers of research . . .

ciency theory following Serrin and the eigenfunction solutions for nonlinear problems following Stuart and later workers.)

2. Turbulence, including a careful development of multipoint correlation functions and the von Karman-Howarth equation, spectral energy and transfer functions. Closure techniques, both classical and the recent work of Kraichnan, are considered in substantial detail.

3. Shock phenomena, including the elements of compressible flow and development of shock waves, shock tubes for high temperature research, shock structure, and shock formation in relaxing gases and viscoelastic media.

4. Deformation and flow of viscoelastic materials, including the proper description of fluids with a memory for previous deformation states, methods of determining physical properties, behavior in flow fields with large Weissenberg or Deborah numbers, consequences of finite shear wave propagation, the peculiar effects of vorticity upon stress levels in visco-elastic media and approximations employing a diagonal deformation rate tensor. ---

Topics covered in 1968-69 included the structure of interfaces and surface waves; bubble and droplet formation, motion, and coalescence; low Reynolds number hydrodynamics; turbulence and shock phenomena. Other topics covered in recent years have included two-phase flows of gas-liquid mixtures and fluidization, though the fundamentals of the former area are now usually treated during the first weeks of the regular seminar on that subject and the latter in the second level course on reactor analysis. During the coming year we expect that new faculty additions will enable the inclusion of material on surface tension driven flows and transport at high Knudsen numbers. A recent grant for the strengthening of the department will enable us to bring to the campus distinguished

The courses represents our attempt to provide a background in fluid mechanics which is uniquely of value to the chemical engineer faced with gunks and goos, multiphase flows and instability phenomena, as distinguished from the usual aerodynamics bias of the subject.

from year to year depending upon when an area was last taught and the special interests reflected in the research activities in the department.

In the 1969-70 academic year the following topics were covered:

1. Stability theory, including the linear theory and both exact and approximate solution techniques. (In other years we have also included the nonlinear suffi-

visitors in greater numbers. Prof. G. Marrucci participated in this course in 1968-69 and in 1970-71 the expertise of Prof. V. K. Stokes in the area of liquid crystals and other anisotropic media will enable the presentation of this subject, especially significant for its removal of cobwebs concerning the role of angular momentum and its conservation. In future years we look for

coverage of numerical methods in fluid mechanics in an intense way, biomedical topics and — if current research in several locations is successful — the use of fluid mechanics to control polymeric crystallization processes.

Thus, a Ph.D. candidate with a strong interest in fluid mechanics can move to the frontiers of 7-10 areas, in a painless way, during his tenure. Perhaps even more important than the factual material covered is the clear manner in which a substantial number of complimentary approximation techniques can be brought to bear on various aspects of the subject, and the role and limitations of each. Too, the greatest weaknesses — the simplistic empiricism of almost all constitutive approximations, both thermodynamic and rheological — emerge vividly and focus attention on areas of research in which the chemical engineer is peculiarly well qualified to play a role.

IN SUMMARY, we have attempted to describe the separate roles and goals of our first and second level courses in fluid mechanics. Similarly structured is the presentation of heat and mass transfer, chemical kinetics and reactor design, and for the first time this year, thermodynamics. We believe such multi-level instruction to be important and exciting.

BIOENGINEERING: Leonard

(Continued from page 175)

are done, mostly by the students in small groups, using modern equipment.

Participating in this much biological course work takes about one-half of a student's time for a calendar year. How he spends the balance of this time may importantly influence his professional attitude. So much biological course work is not intended to convert the engineer into a biological scientist. Contact with and progress within the engineering curriculum should be maintained during this period. However, challenging courses in engineering which do not relate to bioengineering create a disturbing intellectual bifurcation in students at this stage. At least two semester-courses which integrate engineering with biology should be available. Such courses are difficult to construct. At Columbia we have used a bioengineering seminar at which contemporary research problems are discussed, about 50% by guest speakers, 25% by students

in research, and 15% by engineering faculty. The seminar is school-wide, but because of the particular composition of interests at Columbia, more than half of the subjects are of direct interest to those with chemical engineering backgrounds. So broadly based a seminar might not be effective in other circumstances. Frequently, students will be beginning a thesis or research paper while taking biological courses. This effort may provoke satisfactory integration of concepts, but at a high cost in faculty time.

AT WHAT STAGE of education should such studies be undertaken? At present it seems best to begin at the master's level. To satisfy minimum point requirements in engineering at many schools, the M.S. program may need to be extended in time and credits. However only physiology need be taken at the graduate level, so that it is possible for the undergraduate to anticipate much of the biological science desideratum. It is, of course, also possible to commence biological studies at a later stage. In each of these suboptimal situations, however, it is substantially more difficult to achieve integration of engineering and biological concepts.

Artificial organs technology has been, for us, a valuable educational vehicle. These devices can be considered with only limited amounts of biological background although the treatment becomes more sophisticated and more satisfactory as the available background increases. We have given a one-semester course accessible to senior chemical engineers but designed to be challenging at the master's level. All possible emphasis is put on the integration of engineering concepts and biological fact. The behavior of blood in extracorporeal circuits is considered in terms of rheology, shear-susceptibility, undesired reactions with artificial surfaces, and problems of intraphase transport. Comparisons are made with intracorporeal circumstances and the problems, surgical and mechanical, of acute and chronic cannulation are considered. Primary and secondary specifications are established for cardiac replacement and assistance devices, comparing actual prostheses and their rationales with the heart and the characteristics and demands of the circulatory system. The artificial kidney and blood-gas exchangers are introduced as artificial capillary beds; specifications are established for transport capability, allowable volume, and pressure-flow characteristics, with recognition of how limitations imposed by con-

temporary technology prevent full reproduction of the performance of the natural counterpart.

Such a course meets several educational goals. Foremost, it provides an integrating experience the importance of which has already been stressed here. It also gives undergraduates an elective by which they can learn something of bioengineering. It demonstrates, as do other 'applications' courses in chemical engineering, the breadth of the field. It shows that the configuration of natural organs may lead to improvements in design of artificial devices even for industrial purposes. Finally such a course is often audited, seemingly profitably, by members of the biological science and medical communities and thus offers a chance to return an educational debt incurred through the many engineering students who enroll in courses in the biological sciences.

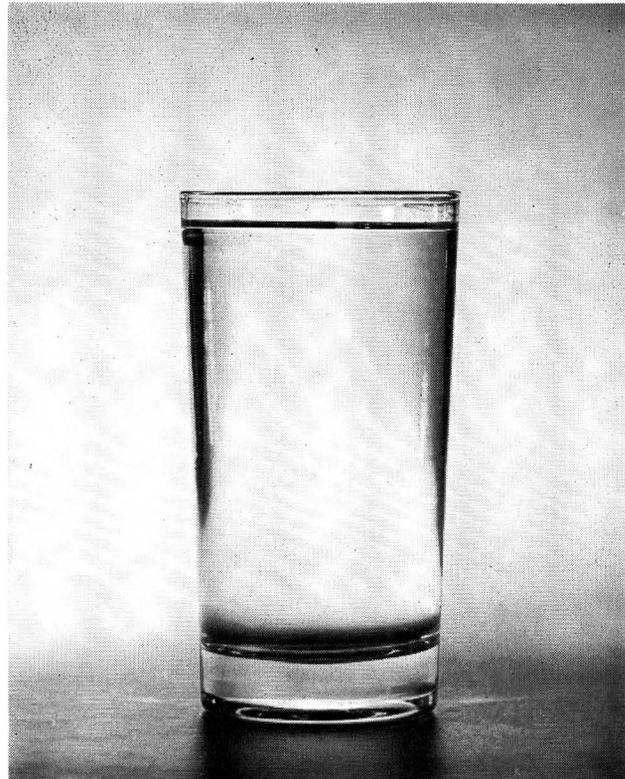
NO DISCUSSION of contemporary education for the chemical engineer interested in bioengineering should close without recognition of the extraordinary educational value of research in a field so new that much of contemporary knowledge and practice cannot yet be made available in course work. All chemical engineering M.S. students at Columbia must submit a master's thesis. For those interested in bioengineering this requirement always means exposure to a biological, usually medical, environment and frequent consultation with one or more biological scientists or academic physicians. These often serve as co-sponsors of the research.

What happens to chemical engineers who emphasize bioengineering in their graduate training? There is a small but growing artificial organs industry comprised with but a few exceptions of small companies. Perhaps a score of M.S. graduate could find employment in this industry each year. The extramural contract programs of the National Heart and Lung Institute and the National Institute of Arthritis and Metabolic Diseases put some tens of millions of dollars per year into private research organizations and thus provide employment opportunities for perhaps another twenty graduates at the master's or doctoral level. Paramedical industries have developed with little help from bioengineers (but not other engineers working on problems which could be divorced from their ultimate environment such as packaging, filtration of parenteral fluids, stress analysis of

surgical instruments, design of disposable injection equipment and low-noise amplifiers for biological signals). Increasingly, these industries are seeing the need for engineers to solve problems which are much less easily separable from the biological environment, but it is difficult to say how rapidly such opportunities will become available. Perhaps, again, a score or more jobs, mostly at the M.S. level, is all that can be expected each year in the early '70's. Other openings are provided by the biological component of the United States' space effort. Both research and development are included, but the uncertain scope and composition of this effort over the next several years makes quantitative predictions most uncertain. Most uncertain of all are opportunities in the country's enormous biological research establishment where most holders of the bioengineering doctorate will seek careers. The establishment behaves insularly, even among the biological sciences; but the early successes of interdisciplinary projects, the favorable bias of the federal granting agencies toward bioengineering, the tendency of bioengineers to create a research establishment for themselves, and the persistent governmental emphasis on reduction of biological knowledge to deliver health care all indicate, albeit uncertainly, an increasing job market.

The compromise which is contemporary bioengineering education should not persist. The biological sciences are lumbering slowly toward a solid basis in physical science. As biological science courses become more quantitative and conceptual they will become more acceptable as intrinsic parts of an engineering curriculum. Chemical engineering, already a discipline which is concerned with more than the chemical and petroleum industries, will offer a wider set of examples in its course offerings, ultimately including, as a matter of course, some from living systems. Unpredictable factors will determine whether most engineering schools ultimately offer curricula in bioengineering, but it appears certain that the stronger programs for the foreseeable future will be less sweeping and more concentrated. A wise but enthusiastic espousal of bioengineering as an option in chemical engineering departments offers the profession an unparalleled opportunity to expand its scope meaningfully, to study new material with potential value for all applications of the profession, and to broaden its service to humanity.

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A Course on

SEPARATION PROCESSES

JOHN E. POWERS
University of Michigan
Ann Arbor, Michigan

ONE FASCINATING ASPECT of chemical engineering is the tremendously wide variety of regions of interest which are incorporated as part of the general field. Two broad areas of interest serve to distinguish the chemical engineer from chemists and other engineers: the ability to design processes involving chemical reactors and separation processes. Indeed the cost of most chemical and petroleum plants (exclusive of utilities) are principally attributable to these two categories. In many cases plant costs will be 5-20 percent for reactors and 80-95 percent for a variety of separation processes including feed preparation and product recovery.

There are a large number of basic separation processes and a much larger number of generic names applied in the field. There appears to be no limit in the variations that can be applied to develop new processes that are basically different or to improve existing processes. Indeed, the field of separation processes has been called an "inventor's paradise."

DESIGN OF SEPARATION processes involves a considerable amount of ingenuity and synthesis. Many of the basic principles to be applied are currently taught under the general headings of heat, mass and momentum transfer. However, other aspects of equal importance are not usually taught in basic courses. For example, one must consider how a small separation achieved in one unit can be increased to attain a product of specified purity. Cascading and compounding of separation units involve knowledge and experience beyond that of basic fundamentals. As mentioned, design of separation processes involves both synthesis and ingenuity. Therefore a course in the subject should properly stress the former and illustrate the latter. The courses in separation processes at the University of Michigan are designed to achieve these objectives.

Rather than teach how to design a number of different separation processes, an attempt is made to teach an approach to the design of separation



John E. Powers was born in Wilkensburg, Pennsylvania, October 12, 1927 and graduated from the University of Michigan in 1951. He was awarded his Ph.D. degree from the University of California in 1954 and then worked for Shell Development Company in Emeryville, California. He joined the faculty of the University of Oklahoma in 1956. He received a National Science Foundation Senior Postdoctoral Fellowship 1962-63, studying crystallization with Dr. H. Schildknecht at Erlangen University in Germany. Since returning to Michigan in 1963 he has been responsible for the graduate and undergraduate courses in separation processes, primarily crystallization. Dr. Powers is also co-director with Dr. D. L. Katz of the University of Michigan Enthalpy Research Laboratory.

ration processes in general. The procedure is broken down into two aspects: 1) mathematical modeling of the fundamental process unit taking into account its mode of operation; 2) methods of increasing the separation achieved either by joining together a number of process units (cascading) or incorporating some procedure to enhance the separation achieved within a single unit (complexing).

Modeling. Emphasis is placed on an understanding of the basic principle underlying the separation and the constraints imposed on the separation by the mode of operation. Several broad classifications are developed to stress different types of basic principles. For example, it is generally important to recognize whether the basic separation takes place within a single phase or results from a concentration difference between two phases in equilibrium. In combination, one must consider whether or not a barrier is required to achieve the separation. For example, thermal diffusion is one example of a separation that occurs within a single phase without using

Design of separation processes involves both synthesis and ingenuity, therefore a course in the subject should properly stress the former and illustrate the latter.

a barrier whereas gaseous diffusion and permeation are single-phase processes that require a barrier. Similarly distillation does not utilize a barrier but depends on a difference in concentration between two phases. Filtration is a two-phase separation process that makes use of a barrier. Modeling of a variety of processes in each category emphasizes a general approach.

Mathematical modeling of individual units is also influenced a great deal by the mode of operation. The mathematical constraints that are applied to satisfy the mass, energy, and momentum balances will depend on whether the process is batch and transient, a flow process at steady state or a hybrid involving unsteady-state operation of a flow process. In all cases it is desirable to develop a mathematical model of the basic unit that yields a descriptive equation of reasonable form. This is especially important if the individual units are to be joined into a cascade. Therefore a number of simplifying assumptions that have proven to yield suitable design equations are summarized in general form and emphasized by applying to a number of different processes with various modes of operation.

In most separation processes, the basic effect is insufficient to produce the desired separation. Therefore some processing scheme must be developed to enhance the separation and mathematical techniques need to be developed to permit estimation of the total separation achieved and to apply optimization techniques if necessary. In many cases individual basic units are joined together. The most familiar example is a series of distillation stages joined to form a distillation column. The use of reflux and the concepts of limitations such as minimum stages and minimum reflux are developed. In some cases such as gaseous diffusion the separations achieved in any stage are so small, the time to achieve operating conditions with the usual cascading arrangements are so long and the costs so high that advanced cascade theory must be applied to attain a workable design. Such an application is illustrated emphasizing general principles of advanced cascade design.

It is sometimes possible to enhance a separation within a single unit. This usually involves countercurrent flow within the unit. Packed column absorption and extraction provide illus-

tration of such techniques involving contacting of two phases. Fixed bed operation including chromatographic separations are considered in this same category. Application of these general principles to separations achieved within one phase usually involves laminar flow brought about by density differences within the single phase in combination with a gravitational or centrifugal field and are therefore subject to mathematical analysis. Thermogravitational thermal diffusion and gas centrifugation illustrate this approach.

SEPARATION PROCESSES involve a bewildering variety of approaches both from the point of view of the basic principles to be applied, and the mode of operation including the possibilities of cascading and complexing. Therefore it is usually possible to illustrate the principles of a general approach to the design of separation processes by providing examples and home problems based on a wide variety of basic techniques. During the course, examples are drawn from filtration, leaching, extraction, distillation, absorption, adsorption, permeation, gaseous diffusion, crystallization, thermal diffusion, chromatography, etc. Examinations are designed to test the students' ability to synthesize a solution to a problem involving a basic approach and/or mode of operation which has not been treated in the lectures, home problems or outside reading. The response has been most gratifying.

Up until the past year the graduate course on separation processes has been elective with good attendance. At present the course is required of all first year graduate students.

ERRATA

SOME CURRENT STUDIES IN LIQUID STATE
PHYSICS
DIELECTRIC AND CRITICAL STATE PHENOMENA
C. J. PINGS

California Institute of Technology
Pasadena, California

In Table I of the paper, "Some Current Dielectric Studies in Liquid State Physics, 2. Dielectric and Critical State Phenomena," by C. J. Pings [CEE, 4, 98 (1970)], the second row of entries should be labeled "Primitive Expt.," and the fourth row should be "Refined Expt."

Also the following footnote was omitted:

Work supported by the Chemistry Directorate of the Air Force Office of Scientific Research.

A Course in

HEAT AND MASS TRANSFER

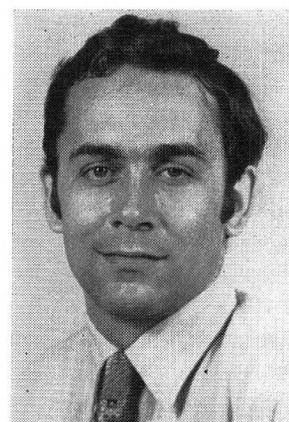
H. L. TOOR and D. W. CONDIFF

*Carnegie-Mellon University
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THIS COURSE HAS traditionally been taken by first year graduate students in Chemical Engineering, whether or not they intend to terminate at the Master's level or continue towards the doctorate. It is offered in the spring semester and is preceded in the fall semester by a fluid mechanics course, although students starting in the spring semester reverse the order with little apparent trauma.

The prime object of the course is to make a step change in the student's perception of and approach to the subject. Undergraduates are comfortable at a more or less elementary level of approach to heat and mass transfer. What is meant by comfortable is that they can define and solve transport problems which fit into this framework with a sense of security and, depending upon their undergraduate preparation, they have some kind of a feeling that there are other ways of approaching the same problems. They are rarely secure with these other approaches, however.

There are two dangers which arise in attempting to effect too rapid a change in a student's viewpoint. At one extreme he may not develop enough of a grasp of the more sophisticated viewpoint to feel secure with it. In his later work this student will fall back on the approach he is secure with (his undergraduate approach) and he will attempt to force problems he faces into this narrower framework. This student may make a fine engineer under some circumstances, but he has probably wasted much of his time in the course. At the other extreme the student decides all situations must be treated with the powerful new tools he has mastered. This student practices overkill at all opportunities and makes a mediocre engineer. Thus a student must not just understand the new approaches introduced in the course, he must also understand when and when not to use them. Although the course content is primarily engi-



Herbert L. Toor was born June 22, 1927. He received his B.S. from Drexel Institute of Technology; his M.S. and Ph.D. from Northwestern University. He has been employed as Research Chemist, Monsanto Chemicals, Limited 1952-1953. He is presently Professor of Chemical Engineering (1961-) and Head of the Department of Chemical Engineering (1965-). He is the author of numerous papers on diffusion and a recipient of the Alan Colburn award of the AIChE. (Left)

Duane Condiff received his Ph.D. in Chemical Engineering from the University of Minnesota in 1965. Following this he spent one year doing post doctoral research in Theoretical Chemistry at the University of Wisconsin, and has been teaching Chemical Engineering at Carnegie-Mellon University for four years. His major research is conducted in the field of non-equilibrium statistical mechanics with emphasis upon applications to the molecular and particulate theories of transport.

neering science, both words need to be taken seriously.

It seems that the best way for a student to both learn new material and to get it in perspective is to solve lots of problems, and that is just what he does in the course. A mixture of various kinds of problems is used; exercises to help learn new material, frequently out of BSL, problems which require skillful application of the advanced material, problems which can and should be solved by elementary methods. The course meets four hours a week and slightly less than half that time is taken up with discussing problem solutions.

We find BSL to be most useful and although not used as a textbook (there is no real textbook

for the course) students are expected to read and understand almost all the material in that book.

A few general rules. The student should not get bogged down in mathematics, a good physical feel for a situation is crucial; intuition, quick approximations and a feel for magnitudes and dominant effects need encouragement.

For pedagogical purposes it seems to be desirable to cover heat and mass transfer mostly sequentially, and since a good deal (but not all) of the heat transfer material can be carried over to mass transfer, somewhere between one half and two thirds of the first part of the semester is devoted to heat transfer. However, straightforward mass transfer analogies are noted as they arise throughout the first part of the course.

HEAT TRANSFER

The course starts out with a map of the field, a sketch of the various levels of analysis available and a categorization of the levels of analysis needed to handle various types of problems and to answer various types of questions. Review problems of the McAdams type are assigned here and macroscopic balances are briefly reviewed.

Differential balances are discussed from a general viewpoint and special and important examples in heat and mass transfer are obtained rapidly, leaving close examination of assumptions and approximations for later. This leads naturally into the constitutive equations of Fourier and Fick which are examined from various viewpoints. The extension to the general linear system is apparent at this stage but is not pursued until the later part of the course.

One dimensional conduction and convection problems are assigned and discussed during this period and while the student is gaining experience and a feel for the subject, a rather rigorous derivation of the energy equation is presented both for pure components and mixtures with concentration gradients.

A nice way to introduce unsteady conduction is through source solutions and reflection methods which depend heavily on physical concepts, but later emphasis is placed on similarity solutions and Sturm-Liouville methods. Ideas of relaxation times, penetration times and distances, the relationship between Nusselt numbers and temperature profiles are emphasized and then extended from non-flow to flow situations. Dimensional analysis of complex differential equa-

tions is stressed emphasizing the viewpoint that in most situations an engineer neither needs nor is able to obtain complete solutions to the energy equation, but that the equation still remains a powerful tool. The general definition of a Nusselt Number is used to attempt to drive students away from the use of the "film coefficient" terminology, not always with complete success.

Examples of misbehaved Nusselt Numbers, multiphase systems, frictional heat generation, particularly in boundary layers are used to emphasize the limitations of the normal ideas of heat transfer coefficients.

Energy and mass transport in turbulent fluids present their normal difficulties in a course of this type. The best we can do with the available time as far as the modern ideas go, is to sketch some of the basic concepts of statistical turbulence, the state of the art and the relationship of the fine scale to the course scale. The main emphasis is placed on the time averaged equations and eddy diffusivities. The similar mathematical structure of the time averaged equations to the equations used earlier in describing non-turbulent systems is used to show the underlying unity in gradient transport systems. The history of analogies is considered and their relationships to the boundary value viewpoint is stressed. Film and penetration ideas are also discussed briefly at this stage and various engineering applications are treated.

The subjects of radiation and heat transfer with phase changes are treated primarily with problem assignments, mainly because of time constraints.

MASS TRANSFER

The relationship between mass and heat transfer is somewhat like the relationship between the English and American languages; if you know one subject you can get by in the other, but confusion and embarrassment are a consequence of not recognizing the difference between the two.

The general reference velocity is treated as a linear combination of component velocities and the more common reference velocities are then shown to be useful special cases.

The constitutive equation in the simple binary system is first obtained as the linear relationship between the flux and concentration gradient which must go to zero when the system is at a

uniform concentration, and the consequences of using different concentration measures or thermodynamic functions are considered.

The choice of the usual binary diffusivity is shown to be a consequence of its symmetry $D_{12} = D_{21}$ and the inverted form of the diffusion equation, the Stefan-Maxwell form, is used to bring out the essential arbitrariness in the usual formulations.

After considering the relationship between diffusion and random walk processes, Brownian motion, the Stokes-Einstein equation, and the prediction of binary diffusion coefficients, irreversible thermodynamics is used as a convenient way to obtain general forms of the constitutive equations both for heat and mass transfer, and various kinds of coupled systems are considered.

At this point a comparison of the dimensionless energy equation with the dimensionless convective-diffusion equation is carried out to isolate those passive systems (stagnant, laminar, turbulent) in which the solutions to the two equations are the same.

The remainder of the course then concentrates on those mass transfer problems which have no heat transfer analogues or in which the heat transfer analogue has not been considered earlier. Diffusion induced flows, mass transfer with chemical reactions and with phase changes, and multicomponent mass transfer are typically treated. The utility of hydrodynamic models in making engineering estimates of the effect on mass transfer of phenomena such as chemical reactions or convection at a boundary is stressed and then interfacial effects and interphase mass transfer are treated.

The specific material covered in a course of this type is probably less important than the attitude the student carries away; one would like to have him take away the viewpoint that there are powerful tools available, but that they cannot be used blindly, that skill, judgment and common sense are still necessary tools of the engineer.

For the last two years the in-class teaching of graduate heat and mass transfer at C-MU has been handled by D.C. In this endeavor concerted efforts are constantly being made to capture some of the flavor, to uphold the standards, and to take advantage of (and hopefully build upon) the techniques and philosophy of the course as previously taught by Professor Toor. In addition to this tradition, the instructor has

had the benefits of material from two excellent series of courses in heat and mass transfer taught in the sixties at the University of Minnesota by Professor W. Ranz and by Professor A. G. Fredrickson. In the latter case, the courses were taken by Dr. Clarence Miller of C-MU, to whom we are grateful for making available to us his extremely fine set of notes.

Underlying the structure of our current course is a continued stress of theoretical fundamentals and a liberal dosage of assigned practice problems. The student has to learn how to apply the existing methods, but he also has to and wants to understand why they work; and he must be able to judge whether an approach to a particular problem is applicable or inapplicable, or unnecessarily elaborate, or not sufficiently exact for the purposes at hand. For the development of this type of judgment there is, of course, no substitute for the experience of problem solving; but without the added guidance of a thorough understanding of fundamentals, the development of such judgment would surely be severely retarded.

The nucleus of assigned reading for the course continues to be the material of parts II and III of BSL, which the student studies concurrently, or reviews in detail as the case may be. At present most of the students enrolling in the course have had a thorough exposure to dyadics and tensors in the "fluids" course taught the previous semester by Professor Brenner, and this background is utilized to advantage in establishing the compact forms of the general macroscopic equations of transport.

However, this is worked up to gradually. The course begins with the qualitative discussion of physical mechanisms of bulk phase transport from the macroscopic, microscopic, and what we have come to call the "micro-macroscopic" points of view. In the macroscopic view, the distinction is drawn between convective, radiative, and diffusive types of transport with emphasis upon the need for constitutive relations in the latter instance. Here the difference between definition and a physical law is discussed, and followed up by a description of the role of thermodynamic limitations. Then a review of the scalar and invariant formulations of the basic transport laws of Fourier, Fick, and Newton is provided with some attention given to the physical notion of an anisotropic medium.

In the microscopic picture, discussion is lim-

. . . Examples of misbehaved Nusselt numbers . . . are used to emphasize the limitations of the normal ideas of heat transfer coefficients.

ited for this course to a qualitative description of the origins of kinetic and collisional transfer contributions to the fluxes, their relative importance in gases, liquids, and solids, the philosophical inadequacies and "ball park" relevancies of the mean free path theory of constitutive relations, and the important role of rigorous non equilibrium statistical mechanics in this connection. When time permits at this stage of the introduction, the understanding of the microscopic picture is augmented by a lecture surveying the several angles to the theory of Brownian motion.

For the micromacroscopic mechanisms, i.e., for random and difficult to detail motions of small but macroscopic fluid elements, a common thread is woven through the ideas of turbulent eddy diffusivities, dispersion in flow through porous media, etc. The analogy of these physical mechanisms to gas kinetic fluxes is also brought out. These points are illustrated by means of several examples. The first is an estimate on the level of a mean free path approach, of the radial dispersion coefficient for mixing in the flow of fluid through a bed packed randomly with spherical pellets. A second example discussed is a detailed mean free path type "ball park" estimate of the effective transverse thermal conductivity due to the mixing in the wakes of small gas bubbles rising steadily through a liquid.

The student's coverage of shell balance problems (BSL Chapter 9) affords an occasion to discuss the basis of flat (temperature) profile models. This too is done within the context of examples. One of these is the model of a cylindrical infrared heat filter with heat radiation passing longitudinally while being partially absorbed according to Lambert's Law. In a first pass at the problem the sides are taken to be perfectly insulated, a flat transverse temperature profile is assumed, and with the use of external heat transfer coefficients at the ends, the equation for one dimensional heat conduction with source is obtained by a shell balance and solved. In a second pass we allow for heat loss at the sides with a finite external resistance, but still employ a flat temperature profile model. In a third pass, the partial differential equation for steady state two dimensional conduction with source is obtained by a shell balance, and the complete boundary value problem is identified. The

problem is rendered dimensionless and three independent dimensionless parameters are identified along with the dimensionless variables. Without solving the boundary value problem, the solution is shown to be equivalent to the flat temperature profile models of the first two passes when appropriately selected dimensionless parameters approach zero. This is done in the second instance by means of a regular perturbation analysis which is employed to derive the flat profile model directly. In another example, a similar perturbation analysis of a more exact problem is used to derive the flat profile model which is outlined in §9.7 of BSL for conduction in a rectangular cooling fin.

In all of such analyses, the mathematical methods per se are relegated to positions of somewhat lesser significance in favor of the lessons to be gleaned from the results of the derivations. Thus, the value of studying the problem in non dimensional form is emphasized along with the importance of recognizing a priori the dimensionless criteria for the approximate validity of flat temperature profile models. In this same vein, the assigned problems are oriented towards using such models with an intuitive recognition of the criteria for their validity.

For purposes of contrast, the general to specific approach is employed in part for treating the problem of forced convection heat transfer to a fluid engaging in turbulent or laminar flow through a conduit. Thus, the equation of change for cup mixing temperature is utilized to explain physically why the asymptotic problem with *constant wall heat flux* is unique in its simplicity. Then for this boundary condition the expression for the asymptotic internal heat transfer coefficient for pipe flow in terms of multiple integrals involving velocity profile and position dependent diffusivities is derived. Using this, the result for laminar flow of a Newtonian fluid (BSL, §9.8) as well as those for plug flow and for flow of an Ellis-model fluid are recovered as special cases by straightforward integrations. Extensions to treat the effect of compressibility and/or viscous dissipation have been used in examinations.

Proceeding to the general macroscopic transport equations, a vector tensor derivation is given for the general generic form of such equations.

(Continued on page 195)

A Course in

BIOCHEMICAL ENGINEERING

GEORGE T. TSAO

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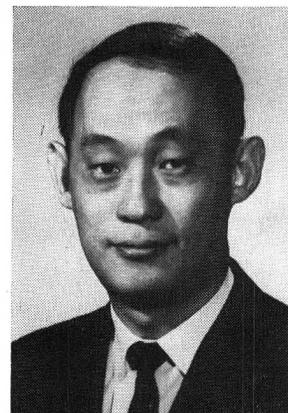
I. The Need

BIOCHEMICAL INDUSTRIES are those involving biochemical and microbiological processes. The oldest example is fermentation by which a large number of chemicals and pharmaceuticals can be produced. Industrial food processing is another area in which a chemical engineer is often required to consider biochemical and microbiological problems such as preservation of taste, flavor and nutritional value and prevention of spoilage.

Besides the normal growth in fermentation and certain sections of food processing and pharmaceutical industries, there are three areas which are currently stimulating additional interest in learning biochemical engineering. They are briefly described below.

Enzyme Engineering: Enzymes are proteins which catalyze biochemical reactions. Enzymes are, in fact, excellent catalysts judging from their high specificity and rapid reaction rates. Recently, enzymes are becoming more important not only in biochemical laboratories and in medical applications but as industrial catalysts in chemical processing. The major factors currently restraining the broad application of enzymes in industry are the high cost and the relative unstable nature of enzymes. More efficient methods of enzyme production and purification, better methods in enzyme recycling and better engineering in kinetics and reactor design will require the talents of chemical engineers who have had training in biochemical engineering.

Single Cell Protein: The cells of microorganisms contain high levels of protein which are commonly known as the single cell protein (SCP). Production of SCP from carbohydrates and more recently from hydrocarbons has been considered most promising in solving the problem of immediate and long range world food supply. Microorganisms not only can convert non-food materials such as hydrocarbons, ammonia, and potassium phosphates into edible proteins but also can



George T. Tsao received a B.S. degree from National Taiwan University in 1953, a M.S. degree from University of Florida in 1956 and a Ph.D. degree from University of Michigan in 1960, all in Chemical Engineering. He joined Iowa State University in November, 1966 as an associate professor and was promoted to the rank of full professor in July, 1970. Dr. Tsao's teaching and research interests are in the areas of biochemical engineering, enzyme technology and biological waste treatment. Before joining Iowa State, he was an assistant director of research of Union Starch & Refining Co., a Division of Miles Laboratories, Inc.

make the conversion in extremely high rates and with good efficiency. Dynamics of cell growth processes and oxygen absorption in multiple-phase hydrocarbon fermentations are all challenging problems of biochemical engineering.

Biological Waste Treatment: In water pollution, the problem of oxygen supply is of great importance. The oxygen solubility in water is about 10 milligrams per liter. When water is polluted with, say, one gram of glucose, the microbiological activity stimulated by the presence of this gram of food is sufficient to exhaust dissolved oxygen in more than 100 liters of water. Unless re-absorption of oxygen from the atmosphere is fast enough, fish and other marine organisms will receive irreversible damage. In (micro-) biological waste treatment, the contaminated water is processed through highly efficient gas-liquid contactors to absorb oxygen to biologically convert all the biodegradable pollutants into either escapable gases or filterable solid cell mass. Thus, a good portion of the water pollution control technology centers around microbiological activities and particularly biological oxidation. This is true in pollution damage to water resources and also true in waste treatment. With additional training in biochemical engineering, a chemical engineer is probably the best qualified engineer in pollution abatement.

A course in biochemical engineering covers the engineering aspects of biochemical and microbiological processes . . . It provides supplementary training to ChE students . . .

II. The General Philosophy

IN ADDITION TO ALL regular chemical engineering subjects including stoichiometry, unit operations, transport phenomena, thermodynamics, kinetics and process control, chemical engineers serving biochemical industries can work more effectively if they also have training in the fundamentals of biochemical engineering. Most chemical engineering students have taken non-major courses in mathematics, physics, and chemistry. For those whose work will involve biochemical and microbiological processes, certain additional exposure to elementary biochemistry and microbiology will be helpful.

Biochemical engineering is not a separate discipline from chemical engineering. It is neither "condensed biochemistry and microbiology" made easy for chemical engineers. A course in biochemical engineering covers rather the engineering aspects of biochemical and microbiological processes that are not normally covered in regular chemical engineering courses. It is to provide supplementary training to chemical engineering students so that they are better prepared as chemical engineers for work that involves biological and microbiological processes. A biochemical engineering course covers either (1) topics unique to biochemical and microbiological processes such as microbial cell growth or (2) those chemical engineering topics that are of particular importance to biochemical industries such as gas-liquid interfacial mass transfer of oxygen.

A course entitled Biochemical Engineering has been offered to graduate students and qualified seniors at Iowa State University to provide the supplementary training as described above. For those graduate students who intend to become specialized in biochemical engineering, additional training is of course needed.

An additional objective of this course is to arouse awareness and stimulate interest in biochemical engineering research among chemical engineering students. There have been very few universities offering such training for chemical engineers, although there is a trend toward greater interest in this area. This is quite in step with the current trend towards interdisciplinary studies.

FALL 1970

III. Outline of the Course

Course title: Biochemical Engineering

Textbook: none (There is a lack of a suitable textbook.)

Prerequisites:

- (1) No previous training in biochemistry or microbiology is assumed. A sufficient coverage of the basics of biochemistry and microbiology is included in this course so as to allow intelligent discussion of the related biochemical engineering problems.
- (2) Graduate students and qualified seniors (have had courses dealing with chemical kinetics and mass transfer) of chemical engineering.
- (3) Non-chemical engineering majors by permission. (note: Qualified students from Departments of Sanitary Engineering, Biochemistry, Bacteriology and Food Technology can often follow this course with some extra help from the instructor on basic chemical engineering principles.

Chapter 1: Basic Biology

1. major microbial cell structures
2. cells and populations
3. DNA and double helix
4. RNA
5. enzymes
6. protein synthesis
7. genetic information

reference: Part 1 "Biochemistry of Bacterial Growes" by J. Mandelstam and K. McQuillen (Wiley, 1968).

Chapter 2: Microbial Cell Growth

1. Quantitation of growth
2. batch growth curve
3. lag phase and its shortening
4. exponential phase
5. mathematical description of growth curve
6. Monod equation and its extensions
7. Perret's growth model
8. Hinshelwood's balanced cell expansion model
9. production of single cell production

reference: Chapters 2, 3 and 5 in "Growth, Function and Regulation in Bacterial Cells" by A. C. R. Dean and Sir Cyril Hinshelwood (Oxford Press, 1966).

Chapter 3: Applied Microbiology and Industrial Fermentation

1. yeast, mold and bacteria
2. basic nutrients
3. pH effect
4. temperature effect
5. classifications: aerobic vs. anaerobic, etc.
6. concept of pure culture and controlled mixed culture
7. design of typical industrial fermentors and accessories

8. identification of areas for engineering investigation (as an introduction to the later chapters)
9. examples of typical industrial fermentation processes

references: Chapters 1 and 2 in "Biochemical and Biological Engineering Science" vol. 1, by N. Blakebrough (Academic press, 1967).

Chapters 1 and 2 "Biochemical Engineering" by S. Aiba, A. E. Humphrey and N. F. Millis (Academic Press, 1965).

Chapter 4: Continuous Process of Cell Growth, Substrate Utilization (Waste Disposal) and Product Formation

1. single stage, perfect mixed cell propagator (chemostat)
2. mathematical equations for cell growth, nutrient depletion and product accumulation
3. concept of wash-out
4. cell recycle and effect on cell yield
5. multiple stage cell propagator
6. design of continuous process—method by leudeking
7. plug flow and non-ideal reactor in cell growth
8. new techniques—concentrated cell population, dialysis cell propagator

references: Chapter 5 in "Biochemical Engineering" by S. Aiba, A. E. Humphrey and N. F. Millis (Academic Press, 1965)
Supplementary handout.

Chapter 5: Enzyme Kinetics

1. enzymes
2. Michaelis-Menten equation
3. equilibrium approach and steady state approach
4. Lineweaver-Burk and other plots
5. Monod equation and Langmuir equation
6. enzyme inhibitions
7. reversible competitive inhibition and Lineweaver-Burk plot
8. multiple and simultaneous enzymatic reactions
9. temperature effect

references: Chapter 6 in "Biochemical and Biological Engineering Science" vol. 1 by N. Blakebrough (Academic Press, 1967).

Chapter 4 in "Enzymes" 2nd ed. by M. Dixon and E. C. Webb (Academic Press, 1964).

Chapter 6: Industrial Enzymology

1. types of enzymes: intracellular vs. extracellular, etc.
2. methods of isolation and purification (grinding, ultrasonics, alcohol precipitation, salting out, etc.)
3. new techniques in enzyme applications (ultrafiltration, enzyme analogs, enzyme insolubilization)
4. available commercial enzymes and applications
5. important industrial enzymatically catalyzed reactions
6. enzymatic starch hydrolysis and glucose isomerase application

references: Chapters 2 and 3 in "Enzymes" 2nd ed. by M. Dixon and E. C. Webb (Academic Press, 1964).
Supplementary handout.

Dynamics of cell growth processes and oxygen absorption . . . are challenging problems of biochemical engineering.

Chapter 7: Energetics and Metabolic Pathways

1. high energy bonds (ATP, etc.)
2. coenzymes
3. concept of pathways
4. outlines of EMP, TCA, pentose pathways
5. amino acid synthesis and protein synthesis
6. beta-oxidation
7. biological oxidation
8. energy from glycolysis
9. anaerobic formation of methane, ethanol, lactic acid and glycerol
10. biological oxidation of Fe, S, and N compounds

references: Part 1 in "Biochemistry of Bacterial Growth" by J. Mendelstam and K. McQuillen (Wiley, 1968).

Supplementary handout.

Chapter 8: Interfacial Mass Transfer

1. oxygen solubility in water
2. BOD
3. methods for measuring dissolved oxygen
4. methods for measuring rate of oxygen absorption
5. empirical correlations for interfacial mass transfer coefficient
6. application of theory of turbulence
7. interfacial mass transfer theories of Whitman, Higbie and Danckwerts
8. effect of absorbing small particles
9. hydrocarbon-aqueous-gaseous multiple phase mass transfer

references: Chapter 5 in "Biochemical and Biological Engineering Science" by N. Blakebrough (Academic Press, 1967).

Book "Gas-Liquid Reactions" by P. V. Danckwerts, (McGraw Hill, 1970).

Chapter 9: Gas-Liquid and Liquid-Liquid Dispersions

1. interfacial area measured by optical methods
2. measured by chemical method of Danckwerts and Sharma
3. Sauter's mean bubble diameter
4. surface area correlations—Weber number
5. gas-liquid contactors and liquid-dispersion equipment
6. power input
7. foam and emulsion

references: Chapter 5 in "Biochemical and Biological Engineering Science" vol. 1 by N. Blakebrough (Academic Press, 1967).

Chapter on "Dispersion" by Resnick and Gal-Or in Advances in Chemical Engineering (Academic Press, 1969).

Chapter 10: Sterilization of Air

1. sterilization by heat due to adiabatic compression
2. use of packed bed
3. theory of Gaden and Humphrey
4. Friedlander's analysis
5. mechanisms of particles removal from air
6. Pelect number
7. correlation of experimental data

references: Chapter 3 in "Biochemical and Biological Engineering Science" vol. 1 by N. Blakebrough

Chapter 11: Sterilization of Liquid

1. chemical methods
2. cationic detergent, ethylene and propylene oxide
3. chlorination in water treatment
4. phenol number
5. sterilization and pasteurization by heat
6. logarithmic death equation
7. Q-10 theory
8. temperature profile and its integration
9. Z-value and F-value
10. continuous sterilization process and equipment
11. inactivation by heat.

reference: Chapter 13 in "Biochemical Engineering" by F. C. Webb (Van Nostrand 1964)
Chapter 8 in "Biochemical Engineering" by S. Aiba, A. E. Humphrey, and N. F. Millis

HEAT & MASS TRANSFER: Toor & Condiff

Toor & Condiff (Continued from page 191)

This form is specialized to obtain the general mass, momentum, and energy balances wherein conservation of mass, Newton's law of mechanics, and the first law of thermodynamics are each identified as a condition on the respective source terms. The assumption of local equilibrium is then introduced and employed to obtain the entropy balance, with identification of the positive definiteness of the source term as the second law of thermodynamics. Then follows a short survey of the highlights of irreversible thermodynamics using polyadics as a means of providing (i) a compact description of the linear laws of transport for an anisotropic medium, and (ii) a demonstration of Curie's theorem as a mathematical consequence of the assumption of isotropic transport coefficient tensors. It is hopefully made "crystal clear" that a violation of Onsager reciprocal relations is not excluded by any of the macroscopic principles.

With the closed and simplified versions of transport equations derived, methods of getting approximate and exact solutions for special heat transfer and analogous mass transfer problems are examined, though somewhat briefly. The

sequence of study starts with the solution of problems categorized as (i) constant wall temperature penetration (BSL 10.R. 9.P, ex. 11.1-1, plug flow past a flat plate, etc.) all treated together by a similarity argument, (ii) constant wall heat flux penetration (BSL ex. 11.2-2, 9.R, etc.) also solved simultaneously by a similarity argument, and (iii) penetration in combination with external wall resistance. For case (iii) the similarity arguments are shown to break down and so the Laplace transform method is introduced, applied here, and pursued a bit further. Next the separation solutions are developed generally in conjunction with a concise survey of the Sturm-Liouville eigenvalue problem. This permits in particular a look at the general solution forms for forced convection heat transfer to fluid flowing in a conduit with boundary conditions of *constant wall temperature* or of transfer in series with an *external resistance* (e.g., the insulated pipe). The relationship of the lead eigenvalue to the asymptotic internal transfer coefficient is established at this point.

The separations solutions, and their special suitability for long time results provides a natural lead into the concept of relaxation time, which in turn is expanded into the ideas of multiple time scale analysis and their use in the justification of quasi steady state (qss) approximations. An example is the estimate of the time required to freeze a can of beer (for simplicity the beer is taken to be water) which is made using a one dimensional qss approximation. This approximation is then shown by a simple comparison of time scales to be necessarily invalid at the initial and final stages of the freezing process. Another example is the qss estimate of the time and distance of fall of an evaporating spherical raindrop with Stokes law drag, heat transfer correlations, and an analogy assumption for heat and mass transfer.

Problems emphasize the use of qss approximations with intuitive understanding of when they would not be accurate. Additional attention is given to problems with transfer across moving boundaries, especially boundaries where phase changes or fast reactions occur. There is a lecture devoted to the convective diffusion towards a rotating disc, and in this discussion the essential boundary-layer like character of the exact solution is brought out. This points the way to a development of boundary layer equations by simplified asymptotic arguments, with the Von

Karman - Pohlhausen integral approximations considered within the broader framework of the method of moments. Condensation problems and the film models are then considered with their limitations discussed. In particular, the Nusselt theory is developed as the simplest conceivable approximation from within the framework of the method of moments.

In treating turbulent transport we aim more for perspective than for completeness. The approach is to first initiate the student by developing one of the penetration models, and then to distribute for reading, copies of the 1968 award lecture of Professor L. E. Scriven, as published in *Chemical Engineering Education*. Discussion is then focused upon the time averaged equations, emphasizing that the literature on turbulence is often concerned with a deeper understanding of the position dependent turbulent diffusivities which we use. Introduced is an idealized concept which we call the "intense turbulence limit." This physical limit concept allows us to tie together several loose ends. Considering the tendencies of relaxation times towards zero at the limit, and the effective quasi steady state behavior of the boundary transition regions, it is argued on grounds more physical than mathematical that at the limit, (i) the asymptotic internal heat transfer coefficients are totally independent of boundary conditions, and (ii) the asymptotic transfer coefficients are reached instantly, i.e., the entrance region approaches zero in size. The tie-in to reality is then made by noting that often in turbulent flow one is operating near the ideal limit, flow of liquid metals being an exception, and that consequently in the use of empirical correlations for design purposes one is seldom concerned about sensitivity of transfer coefficients to boundary conditions. From this we proceed to a review of design calculations, overall balances, and from thence to radiation, all by way of solving problems. Engineering problems of the quick number or quick conclusion variety are interspersed for balance.

In the time remaining a systematic treatment of mass transfer is attempted with emphasis upon problems without heat transfer analogies ("active" as opposed to "passive" transport). The problems include combined heat and mass transfer situations and are quite often built upon assignments prepared by H.L.T. Solutions are later distributed for all assigned problems.

Discussion commences with diffusion kinematics based upon species *velocities* and in terms of these, definitions of arbitrary and the three principal types of convective (reference) velocities, fluxes of species or their energies, entropies, etc., and the arbitrary break up of these fluxes into diffusive and convective contributions. Diffusion laws for concentration diffusion are brought out in terms of relative species velocities, $v_i - v_j$, by means of the component momentum balances. The general Einstein connection between the binary friction and diffusion coefficients then permits conversion, in the binary case, to the doubly invariant forms of Ficks law for arbitrary reference velocity, from which all other forms follow. In the multicomponent case, the reduction of the component momentum balances to the ideal gas Stefan-Maxwell form is then described in similar fashion, and followed by the concentration diffusion laws with respect to the useful volume average reference velocity. Pressure diffusion, thermal diffusion, and diffusion due to externally applied fields are brought in by means of the irreversible thermodynamics for multicomponent systems. Obtained in particular are the general isotropic linear laws for heat and mass transfer in terms of both Onsager and Curtiss-Hirschfelder multicomponent diffusion coefficients, with the theoretical superiority of the mass average reference velocity indicated. (Wherever the going becomes difficult or notation heavy, notes are written out for distribution.) The tie-in to Ficks law for binary systems is then immediately made.

There is emphasis on mass transfer coefficients; there are problems discussed or assigned on film theory, flame models, the corrections for normal mass flow at boundaries, charge transport, a detailed treatment of density gradient centrifugation, etc. Up to now, time has expired before overall balances for multicomponent or active systems could be treated systematically.

Finally, it should be evident that the course is, of necessity, partly survey in nature, and that many of the topics treated, or not treated, warrant a great deal more time. Those students with little prior experience are usually left with a feeling that they have more to learn, but have acquired some facility with and an overview of some of the more advanced methods and ideas, a proper perspective for terminal and continuing students alike.

Three Wiley Texts for Chemical Engineering Students

PROCESS ANALYSIS BY STATISTICAL METHODS

By DAVID M. HIMMELBLAU, University of Texas, Austin, Texas

Both old and new techniques of process evaluation and model-building by statistical methods are described and contrasted in this text-reference.

The "process analysis" of the title refers to the analysis—by statistical techniques—of continuous industrial processes typified by chemical, petroleum or food industries, or of continuous natural processes such as river flows, biological growth and decay. The introduction of these methods into process calculations assures more precise statements about uncertainty factors, and hence to better decision-making.

Highlights are generous illustrative problems and suggested alternatives for practical application if the basic theory should prove inapplicable.

1970 463 pages \$19.95

PROCESS ANALYSIS AND SIMULATION, Volume I: Deterministic Systems

By DAVID HIMMELBLAU, University of Texas; and KENNETH B. BISCHOFF, University of Maryland

First-of-its-kind, timely, this text focuses on *how to build* and *solve* deterministic mathematical models as they are applied to the process industries. In addition to its classroom function, for seniors and graduate-level students in chemical engineering analysis, this volume is of value for control and mechanical engineers.

Demonstrating the solution of various models and submodel systems, the authors present a variety of categorizations with realistic appraisals of utility, stressing the importance of a balanced overall perspective.

The three major sections follow a brief introduction to the vocabulary and philosophy of process analysis. The first part deals with model classification and formulation, the second itemizes individual units or subsystems, and the last section analyzes the complex system formed by a multiplex of subsystems.

Supportive figures and tables, copious problems and a wide range of illustrations from diverse sources augment the text.

1968 348 pages \$17.95

FUNDAMENTALS OF MOMENTUM, HEAT AND MASS TRANSFER

By JAMES R. WELTY, CHARLES E. WICKS, and ROBERT E. WILSON, all of Oregon State University

This is an introductory-level textbook which unifies the traditionally separate fields of momentum transfer (fluid mechanics), heat transfer and mass transfer (diffusion). Comprehension is stressed, so that an understanding of one type of transfer will be used to stimulate understanding of other areas and types of transfer processes.

The transfer process itself is examined as a basic part of engineering curricula, as much a part of fundamental engineering education as thermodynamics or mechanics. Special consideration is given radiant heat transfer and the role of turbulence.

Topics are organized flexibly, so that the material may be considered in either the series or "parallel" approach. Furthermore, each major subdivision of the text is annotated with a chapter supplying specific applications of the textual matter to industrial problems.

1969 697 pages \$16.50



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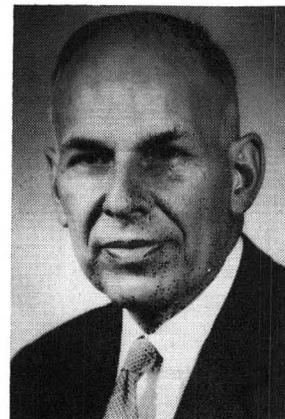
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THE CHEMICAL ENGINEER IN MANAGEMENT

A. L. CONN

*American Oil Company, Whiting, Indiana
President, American Institute of Chemical
Engineers*



PRECISELY, what do we mean by management? A definition that appeals to me is "Management is the process and agency which directs and guides the operations of an organization in the realizing of established aims." Thus, when we refer to management, we are not only talking about a process or operation, but also about an agency, or group of people.

I hardly need to define a chemical engineer for you — but it is interesting that one of Webster's definitions for the verb "engineer" is "to manage," so you can see there may be a certain amount of redundancy in my title; at least in one sense, engineering implies a certain amount of management. In fact, some of my friends who are chemists define the chemical engineer as the man who is sent in to manage the chemists.

AS YOU ARE no doubt aware, the literature is full of the need for more management personnel, for it is claimed that there will soon be an acute shortage of properly trained men, due to the low birth rate in the early 30's. At the same time, the rapid expansion of our technology, bringing with it greater complexity, will increase the need for engineers in management.

In our company, there has always been a large number of technically trained people in management. And believe me, they sometimes do get into the gory details of the operation! The Chairman of the Board and the President of our parent company, Standard Oil of Indiana, are chemical engineers. In addition, two of the three presidents of the other major subsidiaries are technically trained, including a physical chemist and a geologist. And the number of technically trained people in vice presidential and general manager positions is so large that it would have taken me quite awhile to assemble the statistics.

You might think that our company has an unusually large number of technically trained people in top management; however, according to one article, "At least 80% of the top management in the petroleum and chemical companies

Arthur L. Conn is 1970 President of the American Institute of Chemical Engineers. Since 1967 he has been Director of Government Contracts for American Oil Company, Whiting, Indiana. He previously served the AIChE as Vice President in 1969 and as Director from 1966 to 1968. He has also served as Program Committee Chairman and Vice Chairman, as Technical Program Chairman for the Chicago Meeting, and as member of the Awards and Nominating Committees. At American Oil (and at Standard Oil Company of Indiana) he has held positions as Senior Consulting Engineer, Research Coordinator, Director of Process Development, Superintendent of Technical Service and various others. His major accomplishments in process development include fluid catalytic cracking and ultraforming processes and the large scale separation of boron isotopes for the Manhattan Project. He is the author of a number of publications and patents on these subjects.

in the USA received a technical or engineering education as their starting point." And, at the present time, the greatest demand for professional people in these industries is for chemical engineers. The reason for this is that your training includes an ideal combination of the theoretical and practical aspects of chemical processing, together with proper recognition of the importance of economics. Thus, it is clear that people such as yourselves, with technical training in chemical engineering, have excellent opportunities ahead of you. Before discussing these opportunities and how to make the most of them, however, I would imagine that you may have some questions that should be explored first.

At one time or another, each of you must have asked yourself one or more of the following questions: "In order to have a satisfying career and make a contribution to society, should I

Should I point toward management or let others worry about the business and community aspects? . . . At least 80 per cent of the top management in the petroleum and petrochemical industries received a technical or engineering education.

point toward management or should I stay in technical work and let others worry about the business and community aspects of the enterprise?" "How can I decide which area I am best fitted for?" "If I know that I will ultimately get into management, should I get a degree in Business Administration?" "If I don't feel I have enough knowledge to make a choice, what should I do?"

Perhaps I can be of some assistance to you in answering these questions by giving some observations from my own experience. Whether or not one should point toward management or stay in technical work obviously depends on his interests and abilities. If you were a big man on campus — enjoyed managing the swim team or leading the group in the test on the distillation column or found yourself suggesting new goals for your fraternity and ended up as president, the chances are that you have management talent. On the other hand, if you were fascinated by the amount of knowledge you could acquire at college in addition to your regular courses, liked to burn the midnight oil, and enjoyed working out original problems for their own sake, perhaps you should point toward technical work. But these clues should not be taken too seriously. You may have talents along both lines and have had time to concentrate only on one. In any event, it isn't really necessary to make a decision now, so if you feel you don't have enough knowledge to make a choice, don't worry. Almost every large company will start an engineer in a technical position where he will have a chance to learn the business, and sooner or later you will encounter situations that will give you a chance to decide whether or not you have the interest and inclination to manage, or in a rapidly growing company, you may find yourself managing even before you have decided whether or not you want to do so. Conversely, in a well-established, highly technically oriented company, you may find more demand for technical specialization.

As far as I am concerned, either management or technical work can provide an interesting challenge and an opportunity for a real contribution. Many companies have recognized this and have established a dual ladder of promotion — one along administrative lines and the other

along scientific and engineering lines; however, we must recognize that the administrative ladder can lead to the presidency, whereas the top of the technical ladder is usually a staff position, such as senior consulting engineer, scientific adviser or the like. Nevertheless, the differences between management and technical work are not so great or clearcut as may seem at first, and a man may readily change from one to the other. An engineer in management cannot afford to get too far behind in his knowledge of the technical aspects of the work or he will soon find himself making decisions about things that he does not fully understand. Sooner or later, this can trip him up badly. On the other hand, the engineer in technical work, particularly in a senior capacity, may find that his greater technical knowledge puts him in the position of a de facto manager because he knows best what should be done and his suggestions will be followed. In some cases, this may actually call for greater skill in human relations to be able to "call the shots" and still not undermine the authority of the man who is really in charge.

IF YOU HAVE ALREADY made up your mind that you would like to point toward management, I should caution you that just as there are wide variations in abilities and interests among yourselves as students, so there are wide variations in the character of industrial organizations, in the complexity of their operation and in the type of management they require. You may find it a lot easier to make a contribution and earn rapid promotions in the tumbled-down XYZ company than in the prosperous ABC company. Also, just as your interests and abilities will change with the years, so do the needs and the outlook of industrial organizations change. So when you try to pinpoint what you want to be doing ten to twenty years from now, your situation is like that of a man shooting at a moving target with a rifle having a sight needing constant readjustment.

Perhaps that makes it sound a little tougher than it really is. But let's consider first the differences in character of industrial organizations. Let's compare a company that makes cosmetics, toiletries, and related items such as Avon Products, Gillette, or Helene Curtis, with the ABC

company. I won't say which is the ABC company, but I am sure you can guess! The cosmetics company makes a wide variety of products but few of them require complex technical operations. What is more important, the volume of material handled is relatively small and the markup on each item is so large that there is relatively little incentive to try to optimize the engineering steps employed in each operation. Contrast this with an oil company like American, which obtains crude from about 16,000 different wells, sends various crude mixtures to 9 different refineries, and distributes products from these refineries through pipelines, water transportation, and trucks to over 31,000 retail outlets. The volume of material handled is extremely large and the profit per unit volume relatively small, so that there is a tremendous incentive to optimize the entire operation as well as each and every part. Incidentally, ten cents per gallon is the cost of gasoline leaving the refinery; the additional 20-25¢ is almost half taxes, the rest including transportation and dealer service costs.

In the case of the cosmetics company, learning how to manage the business takes relatively little technical knowledge, whereas for the oil company it may take a number of years to become sufficiently familiar with the technical operations to be able to handle a management job. A man working toward management of the first company might do well to take a Master's Degree in Business Administration as soon as he has finished his chemical engineering degree, for he may soon move out of technical work into other

Should one ever refuse a promotion?

If you don't get adverse criticism, does this mean you are doing your job well?

parts of the organization. In the case of the oil company, he might do better to gain a broader technical background, say a Master's or Doctor's degree in chemical engineering, so that he will be in a better position to understand and handle the complexities of the operation. In this case, he might best wait to work for his Master's degree in Business Administration after he had been in the industry for a number of years. This would have several advantages; at that time he would have worked with the company long enough to be sure that he prefers a management job and has the necessary attributes. He would learn the most up-to-date management theories and practice and believe me, they do change! —

and he would have an opportunity to put the theory to direct use. Furthermore, if his superiors have noticed his management talents, he might well be sent by the company to an advanced management school. So you see, the type of industry you plan to enter can have an important effect on how you prepare for it.

Let us now suppose that you have started to work for a company. How can you develop your aptitudes to make the most of your opportunities? Some of you undoubtedly have read some of the large volume of articles and textbooks that have appeared on management. Rather than summarize what you can find there, I would like to mention a few of the commonly accepted "truths" or "cliches" that hold in many situations but can sometimes lead you astray. In doing so, I will take the position of the devil's advocate, and give you some of my observations which show that you can't always go by the book. These are based on situations I have observed in my own company as well as in a number of other companies with which I have had business and professional contacts. I am sure that they apply equally well in government agencies and colleges, for after all, what I am really talking about is working with people — and this is much the same regardless of the specific situation. And believe me, there are many times that the reality can be quite different from the ideal situations that one either hears or reads about.

You have all been advised at one time or another that "If you make sure that you do your present job well, the future will take care of itself." There is a lot of truth in this statement;

by far the most important step you can take toward future advancement is to make sure that you do the job at hand. But is this enough? Certainly, your immediate superior, who is most familiar with your work, is supposed to see that you are properly rewarded. But you can't always count on its working out this way. Supposing for one reason or another he is unable to promote his promising men. He may be working on too small a budget, or he may not get along well with the head of the department, or the department head may have the same problems with his superior, or the company itself may not be doing well. Look at your job as part of a much broader picture. Try to evaluate your boss's

situation as well as your own; try to evaluate the future of the department and the entire company in which you are located. I have sometimes been flabbergasted by the audacity of some young men who have very quickly decided that a particular company was not moving rapidly enough for them, and make a change to improve their opportunities. Some of these men have ultimately landed in top jobs. So, if you are sure you are in a blind alley, do something about it. You may find it necessary to change divisions, departments, or even companies in order to assure yourself of the best possible future. But don't arrive at a conclusion too hastily. On more than one occasion, I have seen a man leave a department or a company and take what appeared to be a much better job, only to find it go sour, while the situation he left suddenly became much brighter — for the man who succeeded him.

You may find it a lot easier to make a contribution to the tumbled-down XYZ company than to the prosperous ABC company.

WHAT SHOULD YOU DO if offered a promotion? I am sure that many would say "Never refuse a promotion — it may be your only chance." Yet I know personally of a number of situations in which promising young men refused promotions that would have taken them away from the work that they liked best, and yet did not suffer. In one case, the man later received numerous promotions in his area of interest, and is now a vice president of a large chemical company. Another man was also very successful and is manager of an important department. So don't feel you have to jump at the first opportunity if it is not in an area to your liking. Study the situation and find out the long-range opportunities in your chosen area, and remember — you will do the best job in the work you enjoy most.

How many times have we heard "Don't be a griper — people will only be annoyed." This may apply to little things, but in cases where the good of the company is involved, the opposite is often true. A man who is sufficiently interested to take the trouble to call to the management's attention a situation that is hurting the company will almost always get a hearing. If the complaint is well considered and is accompanied by constructive suggestions on how to improve the situation, the man will most likely be better off for having

aired his views. And you all know how it is in voluntary organizations — the man who does the griping often gets added responsibility. This can just as often be true in a work situation.

How many times have you heard someone say "As long as they don't give me adverse criticism, I know what I am doing my job well." This may often be true — but I have seen situations where a supervisor sees so many things wrong with what a man is doing that he doesn't know where to begin or how to give him constructive comments. So he says nothing. Other supervisors have become so imbued with the idea of "getting along" with their men, that they haven't developed the ability to give adverse criticism or they may give it to you coated with so much sugar that you don't understand that anything was really wrong. I once had a boss like that — and believe me it was much worse working for him and finding out my mistakes indirectly than working for the type who was difficult to satisfy but told me straight from the shoulder what I had done wrong. So be sure that from time to time you take a good, hard look at your own work; don't assume that lack of criticism necessarily means that your performance is good.

"If you are doing a good job, it isn't necessary to point out your accomplishments to your boss — he has been through the mill and understands the problems you have had to handle." This is something we often tell ourselves — and it has appeal for several reasons. Most engineers are modest individuals and would prefer not to boast about their accomplishments. And — let's face it — most people who go into engineering are not born salesmen. So we usually assume that the boss will know about our accomplishments without our telling him. After all, if we don't tell him, he will hear it from someone else; certainly it is the boss' job to know what is going on in his shop. But, stop for a moment and try to put yourselves in the boss' position. He is being pushed by his superiors for results. He may have been promoted from another area and may not fully understand enough of the details of your job to realize what you have accomplished. In any event, one of the most common errors that I have seen is for an engineer to assume that the boss knows and understands everything that is going on. Frequently, this is not the case. So unless you use one means or another to make sure that he knows the problems you have faced and how you have solved them,

he may not realize how good a job you have done. Diligence is not enough. You have to sell yourself.

THE BOOKS ON MANAGEMENT all say that "authority should be delegated commensurate with responsibility." This is often claimed to be a self-evident truth — after all how can one take full responsibility for the success of a project if he isn't given the authority to carry out all aspects of the job? Everyone agrees to this as a matter of principle — yet I have rarely seen it carried out in practice. Managers are often loath to delegate authority — for many reasons. They may be setting a precedent in one area that they may not want to apply in parallel situations elsewhere; or they may not have full confidence that the man will handle this authority properly. In any event, you will often find yourself in a position where you have to get something done and can't really tell anyone else that he *has* to do this or that for you.

Well, it isn't really as bad as it sounds. If you plan a logical program, discuss it with knowledgeable people and enlist their aid, you will be surprised how, in most cases, they will go along with you and help you get the job done. And so, more often than not, many of us find ourselves doing things for which we have no authority other than the knowledge that this is the best way it can be done and the persuasiveness to get it done that way. So, don't be afraid to move on a project even if you don't have all the authority you feel you need.

If you are given a promotion to replace a man who is going to be working somewhere else, your first reaction will undoubtedly be to discuss the job with your predecessor and find out just how he handled it so that you will cause the least disruption when you take over. This can well be worthwhile, but it should not be a substitute for making your own evaluation of the situation. You may have some knowledge or talent to bring to the job that the other man did not have. You may analyze the situation and conclude that the job can be carried out much better using a different approach. Your boss may not have been completely satisfied with your predecessor and for one reason or another, may not have told you. So don't make the mistake of falling into the same rut; it may be that you were chosen for the job because you were expected to change the situation.

Everyone knows that authority should be commensurate with responsibility . . . but this is rarely carried out in practice . . . the griper often gets added responsibility.

LET US ASSUME you have now made the first step and are now in a supervisory or "management" position. It won't be long before you are wondering how to advance yourself further. Even if you are 100% satisfied, your wife will be wanting a larger house, the kids will be getting close to college age, or something will be impelling you to greater achievement, so you will read books and magazines on management to find out how to get ahead faster. You will undoubtedly find statements such as "concentrate on understanding, judging and dealing with people — this is the most important requirement of an executive." No doubt this is an important requirement. Any person in management soon realizes that everything he accomplishes has to be done through people. Furthermore, it is particularly important for engineers, who are used to dealing with inanimate objects, to acquire the ability to work well with people. But is this the *most* important requirement of a manager? I don't think so.

I have seen managers who did not give too much thought to their people — who did not really try to understand them, and who were not too good at judging them, but who through boldness, initiative and good judgment were able to reach the top. *They got results.* And I have seen men who spent so much of their time concerning themselves about their people — that they did not give enough attention to the economic factors such as promoting a new process, cutting costs, or changing systems for doing business. I don't mean to say that learning to work well with people is not important. It *is*. Nevertheless, your primary responsibility is rarely people oriented. The major function of a corporation is to make a profit and you are expected to get a certain job done at minimum cost or to meet a specific time schedule or the like. And you will not get the next promotion if you are the perfect boss, as far as your men are concerned, but don't help meet the primary objectives as well as someone else.

Another concept that has been promoted strongly by "experts" in management is "make sure that you develop a successor." One management consultant pointed out at a recent meet-

ing that "you can do your present job so well that you become indispensable and can't be promoted." Therefore, he concludes "you should first train a subordinate to do your present job so that you will have someone to take over when the right opportunity presents itself to you." Another expert writing in the Harvard Business Review says "It should be made very clear to the bosses that they will be rated on their success in developing successors." There is no doubt that learning to delegate is an important asset, and that training the men under you can greatly ease your own load and enable the group to get more done. Nevertheless, in some cases, this puts the cart before the horse. In order to win a promotion, you have to demonstrate to your superiors that you can handle a more responsible job. Whether or not you get promoted may be totally unrelated to whether or not you have trained a successor. Your superior may already have someone else in mind as your replacement. In any event, I would suggest that you consider the advice given me many years ago by the vice president for research and development of one of our competitors — "Learn your job well; learn all the aspects of your boss's job; then and *only* then train your successor."

WHAT DOES THIS all add up to? In summary I would say that you don't have to decide now whether or not you should work toward a management position; furthermore, there is much satisfaction to be gained from a predominantly technical career. But if you are sure you are interested in management, and want to work in a large company, it may still be best to take an advanced technical degree rather than one in business administration. Once in industry, or even in government or education, and you decide to head for management, a chemical engineer should recognize that he will be entering an entirely new area loaded with intangibles where his training and background in logical thinking can sometimes lead him astray. There are no completely accepted theories of management that can be studied and learned like a course in distillation or heat transfer. But don't get me wrong. I certainly believe it is wise to learn all you can about good management practices and to apply them in your job wherever possible. At the same time, however, observe carefully how your organization operates, see how these practices are being applied, and above all, make your own evaluations. Remember, that

dealing with people is not always subject to logical analysis; even in engineering decisions the "people" or "political" aspects may prove to be more important than the technical phases. Nevertheless as I mentioned earlier, getting the job done is the most important thing. There are many successful managers who don't follow all the rules, but have the boldness, initiative, and drive to get results.

PROCESS CONTROL: L. B. Koppel

L. B. Koppel (Continued from page 171)

minute process (see reference 1, page 456). When the slower sampling rate was introduced, the value of α was left unchanged; apparently $\alpha = 0.3$ was a blanket recommendation of the computer vendor. But, with the new sampling rate and this value of smoothing constant, the equivalent filter time constant became 8 minutes, much too large for the 10 minute process. In effect, an additional process lag had been unintentionally introduced into the loop, inevitably degrading the performance, and apparently discrediting the use of slower sampling rates. When the value of α was changed to 0.9 to maintain approximately a 1 minute filter time constant, closed loop performance became practically equivalent to that in the original loop with faster sampling, as expected.

Upon reflection, I concluded that I had previously been far too defensive in my attitudes toward teaching graduate-level process control. Very practical technological contributions should result from such teaching. Care must be taken to ensure reasonably complete treatment of theoretical as well as practical ramifications since one could not always predict the sorts of difficulties to be encountered in application. Thus, at a minimum, digital filter theory must be included in a course which discusses sampling frequencies. More importantly, it became clear that recent advances in control theory would not be widely applied to processes until there were more practicing engineers adequately trained in the theory. Some of the theoretical misunderstandings and evasive recommendations which currently exist are illustrated by the discussion on sampling rates in a recent industrial textbook.¹⁵ Typical is the following: "For best results with easy processes, the sampling interval should be as short as practicable."

The subject of sampling rates is clearly not the only potentially practical contribution of con-

trol theory. Many more examples exist; I will illustrate two. Optimal control theory suggests that significant improvement in control of stage-wise processes such as distillation columns can result by recognition of the state concept. Conventional control is based on measurement of the process condition on one plate only i.e., only on the process *output*. The theory shows that the control must be based on the *state* of the process, i.e., on consideration of the condition on each plate. Although measurement of every plate is impractical, measurements on a few plates combined with a process model and any knowledge of past inputs can be used to estimate the state. This estimate based on state will lead to a more rational control of the column. since knowledge of current output is not sufficient to estimate future process behavior. A second example is the observation that optimal controllers never have reset action (unless the performance criterion is artificially altered to force inclusion of reset action). This is often cited as a defect of optimal control theory. Rather, I view this as information from the theory which suggests a logical course for practice. Optimal theory does not yield reset action because it assumes perfect knowledge of the process model and inputs. Therefore, reset action is useful only to correct for imperfect knowledge. This means that only the *unexpected* portion of the response should be integrated in the reset action.

AT THE BEGINNING of the article I estimated that more than two hundred practicing engineers have had graduate level training in process control. Current discussions, both written and oral, indicate that a general impression persists that advanced control concepts are not worthwhile in industry. Therefore, either two hundred is an insufficient number to change this, or advanced control concepts are inherently impractical, or the education of the "two hundred" has not prepared them for this particular "selling" task. I am inclined to accept the last reason. I am concerned because (1) I believe there is as much of potential practical value in graduate courses on process control as in any other area of chemical engineering, and (2) more than in any other area, an impression exists that such courses are primarily useful for generating more academic research.

To meet this concern, I have limited coverage to the three broad topics discussed above — digital control, optimal control, and stability. I

would feel completely successful if each student (1) understood all the theoretical foundations, (2) could read the literature, (3) were stimulated to think of applications of the theory, and (4) were sufficiently confident of the practical value of the theoretical concepts to persevere in the face of apparent contradiction between theory and practice. To the extent that all these cannot be accomplished in one semester, I give priority in the order (4),(3),(2),(1). I attempt to cover in depth only those theoretical aspects which have the highest probability, in my estimation, of helping to achieve item (4). Thus, for example, I cover in some depth sampling theory, and digital filtering theory, while presenting only a heuristic justification of the minimum principle.

I hope that in the next few years, advanced topics in automatic control will win acceptance in industrial applications by virtue of recognizable economic contributions. I am convinced that graduate level education will contribute to this goal.

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CHEMICAL ENGINEERING DIVISION ACTIVITIES

Eighth Annual Lectureship Award to J. M. Smith

The 1970 ASEE Chemical Engineering Division Lecturer was Dr. Joe Mauk Smith of the California Institute of Technology. The purpose of this award lecture is to recognize and encourage outstanding achievement in an important field of fundamental chemical engineering theory or practice. *The 3M Company provides the financial support for this annual lecture award.*

Bestowed annually upon a distinguished engineering educator who delivers the Annual Lecture of the Chemical Engineering Division, the award consists of \$1,000 and an engraved certificate. These were presented to this year's Lecturer, Dr. J. M. Smith at the Annual Chemical Engineering Division Meeting held June 24, 1969 at the Ohio State University. Dr. Smith spoke on "Photochemical Processing — Photo decomposition of Pollutants in Water." A paper based upon his lecture will be published in an early issue of **Chemical Engineering Education**.

PREVIOUS LECTURES

- 1963, A. B. Metzner, University of Delaware, "Non-Newtonian fluids"
- 1964, C. R. Wilke, University of California, "Mass transfer in turbulent flow"
- 1965, Leon Lapidus, Princeton University, "Aspects of modern control theory and application."
- 1966, Octave Levenspiel, Illinois Institute of Technology, "Changing Attitudes to Reactor Design."
- 1967, Andreas Acrivos, Stanford University, "Matched Asymptotic Expansions"
- 1968, L. E. Scriven, University of Minnesota, "Flow and Transfer at Fluid Interfaces"
- 1969, C. J. Pings, California Institute of Technology, "Some Current Studies in Liquid State Physics."

BIOGRAPHICAL SKETCH



Joe Mauk Smith, from Sterling, Colorado, was educated in Applied Chemistry at the California Institute of Technology and in Chemical Engineering at the Massachusetts Institute of Technology.

He has taught in chemical engineering as an Instructor at M.I.T., as an assistant professor at Maryland, as professor at Purdue, as Dean at the University of New Hampshire, as professor and Chairman of Chemical Engineering at Northwestern University, and, currently, as professor and Chairman of the Chemical Engineering Department at the Davis campus of the University of California.

Professor Smith has written two text books, both of which are ranked as standard works: "Introduction to Chemical Engineering Thermodynamics," with H. C. Van Ness, and "Chemical Engineering Kinetics."

Professor Smith's research publications cover a wide range of areas in both basic and applied engineering sciences including heat and mass transfer, reaction kinetics, reactor design, and thermodynamic properties. Recently his research has centered to a significant degree on the engineering aspects of photochemical processes, with emphasis on reactor design and kinetics.

Professor Smith has held distinguished lectureships in the U. S. and in Argentina, Spain, Netherlands, and India. He won William H. Walker Award of the American Institute of Chemical Engineers in 1960.

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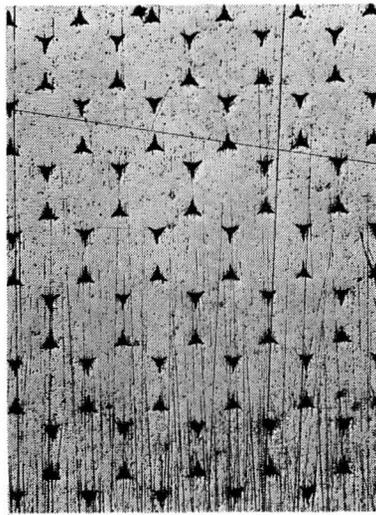
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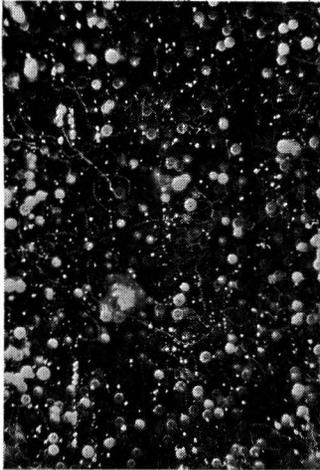
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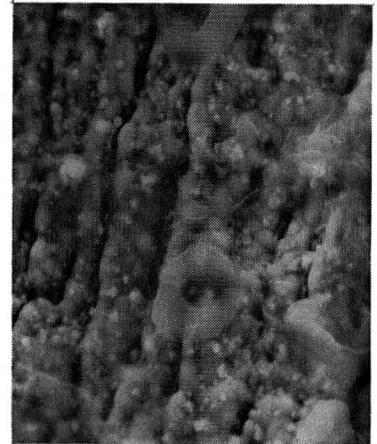


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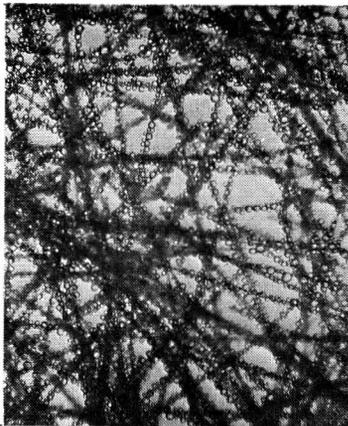


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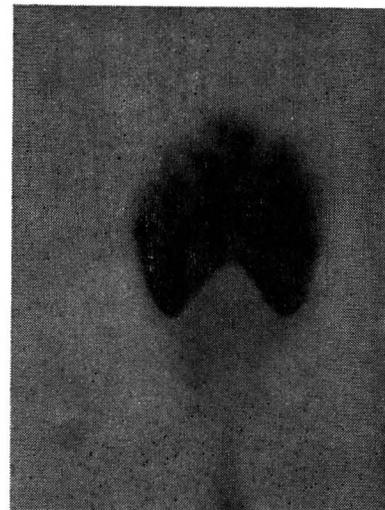
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Henri J. Fenech, Sc.D., Massachusetts Institute of Technology 1959. Professor of nuclear engineering. Research program: Reactor engineering and reactor analysis, heat transfer.

Owen T. Hanna, Ph.D., Purdue Univ. 1961. Associate professor of chemical engineering. Research program: Applications of mathematics in chemical engineering.

A. Edward Profio, Ph.D., Massachusetts Institute of Technology 1963. Associate Professor of Nuclear Engineering. Research program: Reactor experimental physics, neutron shielding, nuclear interaction with matter.

Robert G. Rinker, Ph.D., California Institute of Technology 1959. Associate professor of chemical engineering. Research program: Kinetics and reactor design, energy conversion, air pollution control.

Duncan A. Mellichamp, Ph.D., Purdue Univ. 1964. Assistant professor of chemical engineering. Research program: Dynamics of chemical processes, hybrid computer applications to adaptive and predictive control problems.

Paul G. Mikolaj, Ph.D., California Institute of Technology 1965. Assistant professor of chemical engineering. Research program: Thermodynamics and phase equilibria, structure of liquids and dense gases, oil pollution control.

G. Robert Odette, Ph.D., Massachusetts Institute of Technology 1970. Assistant professor of nuclear engineering. Research program: Radiation effects on properties of materials.

Orville C. Sandall, Ph.D., Univ. of California, Berkeley 1966. Assistant professor of chemical engineering. Research program: Non-Newtonian heat transfer, interphase mass transfer, fluid mechanics of film flow.

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Ph.D. (1964), University of Minnesota
Mathematical methods applied to problems of chemical reactions and transport, process dynamics and control.

L. GARY LEAL, Assistant Professor
Ph.D. (1969), Stanford University
Fluid mechanics; rheology.

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Ph.D. (1955), California Institute of Technology
Liquid state physics and chemistry; statistical mechanics.

BRUCE H. SAGE, Research Associate
Ph.D. (1934), California Institute of Technology
Eng.D. (1953), New Mexico State College.

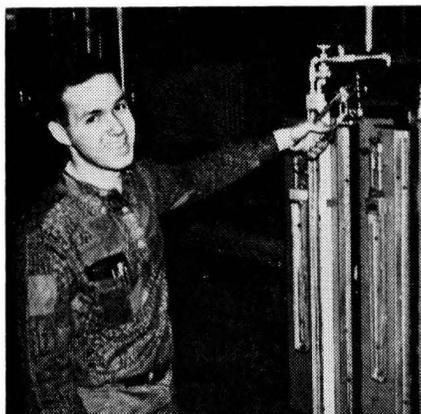
JOHN H. SEINFELD, Associate Professor
Ph.D. (1967), Princeton University
Optimization and systems studies in chemical process control.

FRED H. SHAIR, Associate Professor
Ph.D. (1963), University of California, Berkeley
Phenomena associated with magnetohydrodynamic power generation; chemical reactions and diffusion in electrical discharges.

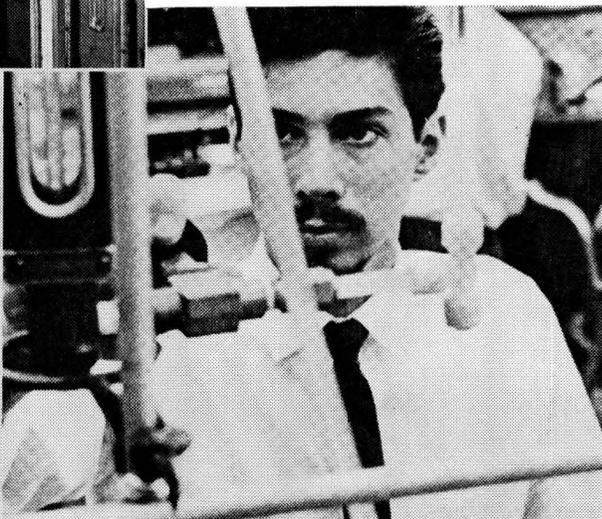
NICHOLAS W. TSCHOEGL, Professor
Ph.D. (1958), University of New South Wales
Mechanical properties of polymeric materials and dilute polymer solutions.

ROBERT W. VAUGHAN, Assistant Professor
Ph.D. (1967), University of Illinois
Solid state chemistry and physics, particularly effects of high pressure.

CASE WESTERN RESERVE UNIVERSITY



CASE INSTITUTE OF TECHNOLOGY, a privately endowed institution with a tradition of excellence in Engineering and Applied Science has long offered a variety of courses and research areas leading to the M.S. and Ph.D. degrees in Chemical Engineering. In 1967 Case Institute and Western Reserve University joined together. The enrollment and endowment make Case Western Reserve University one of the largest private schools in the country.



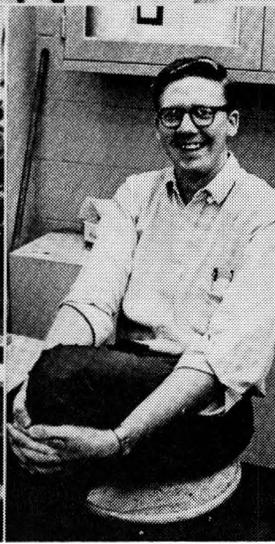
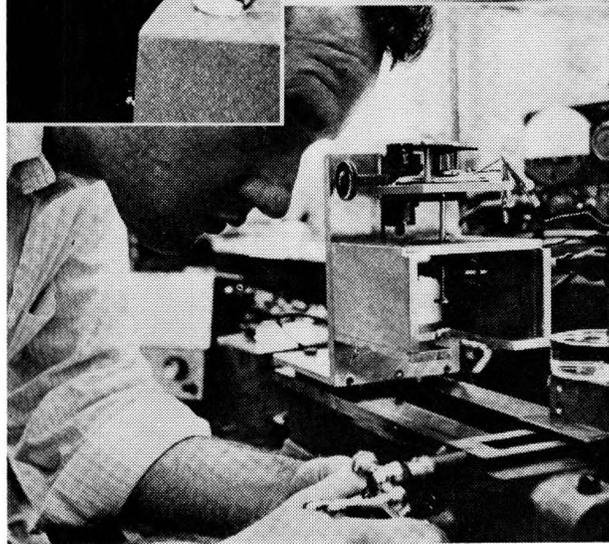
Students interested in graduate work in Chemical Engineering or Applied Chemistry should consider the varied opportunities available in the Chemical Engineering Science Division. Of special interest are strong programs in systems optimization and control, pollution, catalysis and surface chemistry, polymer science and engineering, biomedical engineering, mass transfer, reactor design, and others. Within these broad categories are many individual research projects and course offerings.

FINANCIAL ASSISTANCE

Graduate Assistantships are offered with stipends ranging from \$400 to \$500 per month (depending on background and marital status) from which \$170 per month tuition charge is deducted. Appointments are made by either the academic or the calendar year.

Fellowships and Traineeships are available providing stipends from \$200 to \$350 per month plus full tuition. Additional allowances for teaching and for dependents are included with some.

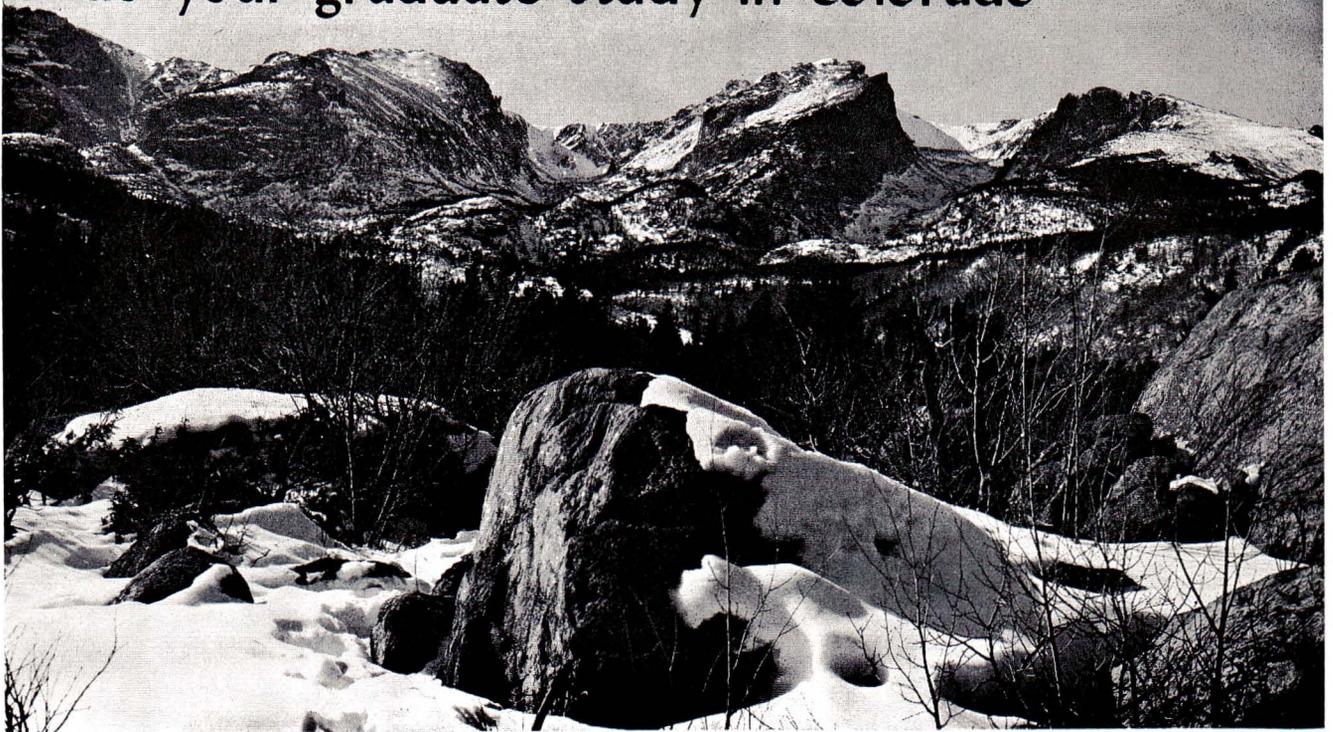
Predocctoral loans of substantial amounts are available.



FOR FURTHER
INFORMATION YOU ARE
INVITED TO WRITE:

ROBERT J. ADLER, Head
Chemical Engineering Science Division
School of Engineering
Case Western Reserve University
University Circle
Cleveland, Ohio 44106

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Financial aid is available: industrial fellowships, NSF traineeships, teaching and research assistantships, and summer support. Graduate student support ranges from \$250-\$400 per month.

For information, contact Dr. J. H. Gary, Department of Chemical and Petroleum-Refining Engineering, Colorado School of Mines, Golden, Colorado 80401.



Teaching & research faculty:

- Dr. J. H. Gary, Head
Petroleum refining
Coal technology
Oil shale research
- Dr. P. F. Dickson
Reactor design
Heat transfer
Asphalt technology
- Dr. F. J. Stermole
Applied mathematics
Engineering economics
Phase change technology
- Dr. J. O. Golden
Fluid mechanics
Heat transfer
Polymers
- Dr. A. J. Kidnay
Thermodynamics
Cryogenics
Mass transfer
- Prof. E. Shimoda
Fluid mechanics
Process control
Computer technology
- Mr. J. Thomas
Electron microscopy
Process control
Instrumentation

Colorado School of Mines Golden, Colorado 80401

THE UNIVERSITY OF CONNECTICUT

Graduate research programs at The University of Connecticut are focused in areas which we believe will be the center of Chemical Engineering activity in the future. As examples: Studies of chemical processes for treatment and purification of polluted water are underway. This program started four years ago, and is presently supported by a \$161,000 grant from the Federal Water Quality Administration. Studies of the bonding of space-age adhesives to metals are also in progress. Concurrent studies of the flow behavior and morphology of polymers are directed toward technological needs of the chemical industry. Catalytic oxidation of automotive air pollutants and the mechanism of catalytic activity are under study. Research is also underway on applications of computers to process simulation and control. These are only a few examples taken from a wide spectrum of programs which are intended to train engineers for the jobs and needs of the future. A favorable faculty-to-student ratio ensures that students receive considerable individual attention, both in courses and research. Courses in environmental engineering, polymer science, etc., are offered in addition to the more conventional courses.



Location

The University is located in a picturesque part of New England, free from the pressures of large urban areas, yet just thirty minutes by car from Hartford, one and a half hours from Boston, and three hours from New York City.

FACULTY

James P. Bell, Sc.D.

Massachusetts Institute of Technology

C. O. Bennett, D.Eng., *Yale University*

Michael B. Cutlip, Ph.D.

University of Colorado

G. Michael Howard, Ph.D.

The University of Connecticut

Herbert E. Klei, Ph.D.

The University of Connecticut

Richard M. Stephenson, Ph.D.

Cornell University

L. F. Stutzman, Ph.D., *U. of Pittsburgh*

Donald W. Sundstrom, Ph.D.

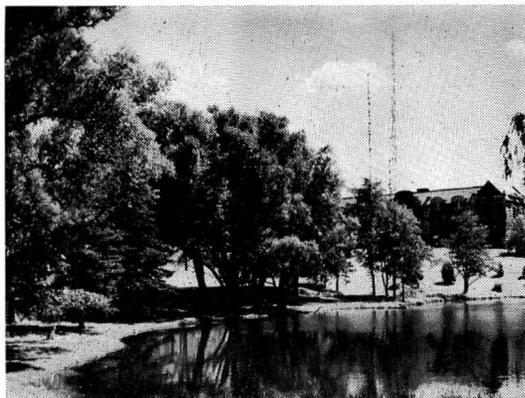
University of Michigan

Financial Aid

Financial aid is provided to qualified graduate students. Stipends range to \$3975 for the academic year. Summer fellowships and assistantships are available.

For further information and applications, write to:

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



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 - Faculty of 19: diversified interests
 - Wide course selection
 - Four degree programs
- Participation in NSF "Center of Excellence" Grant

GRADUATE PROGRAMS IN SCIENCE AND SYSTEMS

Since many of you are interested in industrial careers in development and design, while others intend to teach and do basic research our graduate program is divided into two main areas and several interdisciplinary activities.

CHEMICAL ENGINEERING SCIENCE

Transport phenomena	Fluid dynamics
Thermodynamics	Kinetics
Materials science	Applied Math

CHEMICAL ENGINEERING SYSTEMS

Chemical reaction engineering	Process dynamics
Separations processes	Process control
Computer aided design	Optimization

INTERDISCIPLINARY

Energy conversion	Polymer science
Biomedical	Process economics
Interfacial Phenomena	Bioengineering

DIVERSIFIED DEGREE PROGRAMS

- Master of Engineering with project on design, cost analysis, experimental investigation, or computer study.
- Master of Science with thesis.
- Master of Engineering Pre-Ph.D.
- Doctor of Philosophy.

FALL 1970



BASIC GRADUATE COURSES

Models and Methods • Multidimensional and Discrete Systems • Thermodynamics of Reaction and Phase Equilibria • Transport Phenomena • Process Dynamics • Reactor Design and Optimization (Systems Program) or Chemical Kinetics (Science Program)

TYPICAL ADDITIONAL COURSES

Mathematical Methods in Chemical Engineering • Applied Field Theory • Computer Control of Processes • Optimization Techniques • Transport Properties and Irreversible Thermodynamics • Applied Statistical Mechanics • Statistical Thermodynamics • Interfacial Transport Phenomena • Turbulent Transport Phenomena • Advanced Transport Phenomena • Rheology • Non-Newtonian Fluids Dynamics • Chemical Energy Conversion • Particulate Systems • Applied Fluid Dynamics • Process System Laboratory • Applied Statistics • Process and Plant Design • Process Economy Analysis • Tensor Fields and Fluid Dynamics • Biochemical Engineering • Interfacial Phenomena

Chairman, Chemical Engineering Department
University of Florida
Gainesville, Florida 32601

Please send information on your graduate program to:



REALIZE YOUR POTENTIAL

AT THE UNIVERSITY OF HOUSTON

DIVERSIFIED PROGRAMS . . .

The program is designed to meet the individual needs of the student. Flexibility is maintained by minimizing required courses and by offering a wide variety of degree options; M.S. (undesignated), M.E. (professional, non-thesis degree), M.S. (chemical engineering), Ph.D.

STIMULATING RESEARCH . . .

The research interests of the faculty encompass the entire spectrum of chemical engineering endeavors as well as the newer interdisciplinary areas such as environmental, biomedical oceanographic, systems and urban engineering. The student is free to choose research advisors from other departments of the University.

ESTABLISHED DEPARTMENT . . .

Though relatively young, the Department enjoys an outstanding reputation. In 1968 it was awarded an NSF Center of Excellence Grant, and it has achieved high ratings in the 1970 Carter survey of graduate schools.

EXCELLENT FACILITIES . . .

The Department occupies approximately 52,000 sq. ft. in the modern new Cullen College of Engineering Building. Graduate students are allotted individual offices and laboratories and have free access to the University's 1108 Univac and the College's IBM 360 Model 44 computers.

FINANCIAL ASSISTANCE . . .

Fellowship stipends are available to qualified applicants. These range from \$3,000 to \$5,400 for 12 months, plus tuition and fees.

**INQUIRIES
ARE DIRECTED
TO:**

Head, Graduate Admissions
Department of Chemical Engineering
University of Houston
Houston, Texas 77004

GRADUATE STUDY AND RESEARCH
The Department of Energy Engineering
UNIVERSITY OF ILLINOIS AT CHICAGO CIRCLE



Graduate Programs in
The Department of Energy Engineering
leading to the degrees of
MASTER OF SCIENCE and
DOCTOR OF PHILOSOPHY

Faculty and Research Activities
in the field of
CHEMICAL ENGINEERING

Lyndon R. Babcock,
Ph.D., University of Washington, 1970,
Associate Professor

David S. Hacker,
Ph.D., Northwestern University, 1954,
Associate Professor

James P. Hartnett,
Ph.D., University of California, Berkeley, 1954,
Professor and Head of the Department

John H. Kiefer,
Ph.D., Cornell, 1961,
Associate Professor

G. Ali Mansoori,
Ph.D., University of Oklahoma, 1969,
Assistant Professor

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

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

The Department invites applications for
admission and support from all qualified candidates.
To obtain application forms or to request
further information, please write to:

Air pollution modeling; environmental problems;
polymerization.

High temperature chemical kinetics; combustion and
plasma processes; simultaneous transport phenomena.

Forced convection; mass transfer cooling; combined
radiation-convection problems.

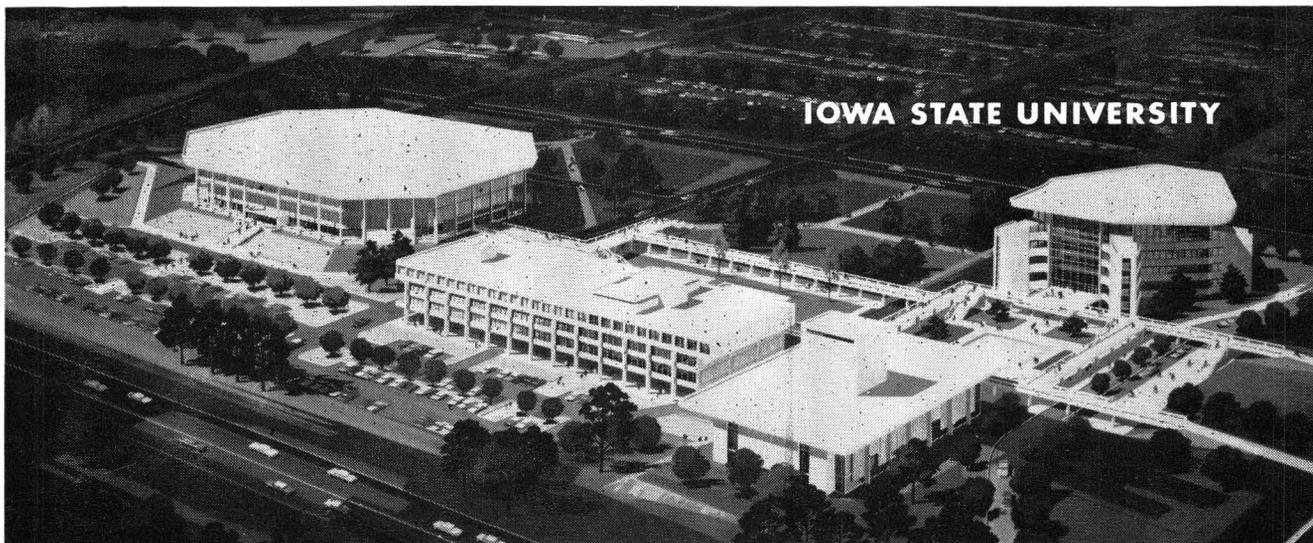
Kinetics of gas reactions; energy transport processes.

Thermodynamics and statistical mechanics of fluids,
solids and solutions; kinetics of liquid reactions.

Transport properties of fluids and solids; thermody-
namics and statistical mechanics; isotope separation.

Catalysis; chemical reaction engineering, optimization;
environmental and pollution problems.

Professor Paul M. Chung, Chairman
The Graduate Committee
Department of Energy Engineering
University of Illinois at Chicago Circle
Box 4348, Chicago, Illinois 60680



Iowa State University in Ames, Iowa, the first school to be established under the 1862 Land Grant Act, has a long tradition of leadership in Engineering and Applied Science. Today it ranks seventh in the nation in Ph.D. degrees granted in Engineering and ninth in degrees in Chemical Engineering. Its College of Engineering is the largest west of the Mississippi River.

To those interested in Chemical Engineering, Iowa State offers a variety of courses and research areas leading to the M.E., M.S. and Ph.D. degrees. The Department of Chemical Engineering is one of the oldest in the United States and enjoys a rich heritage of excellence in teaching and research. The staff numbers 22 and the enrollment consists of 300 undergraduate and 70 graduate students.

In addition to facilities available in a new Chemical Engineering building, research is

conducted in the Ames Laboratory, a National Laboratory of the US Atomic Energy Commission, located on the Iowa State campus. A staff of nearly 1,000 at the Laboratory conducts basic research of long-range interest to the nuclear industry.

Ames lies amid the gently rolling hills of central Iowa. Typical of the picturesque yet modern campus is the new cultural center shown above, now half complete. This fall the Festival of Concerts at the center auditorium was opened by the New York Philharmonic. The 14,000-seat coliseum will host many Big Eight Conference athletic events.

A large variety of assistantships and fellowships are filled each year by new graduate students in Chemical Engineering. Living accommodations are available for single students in a new eight-story graduate dormitory, and for married students in more than 1300 apartments operated by the University.

George Burnet, Head
 Chemical Engineering Department
 Iowa State University
 Ames, Iowa 50010

Please send application forms and further information on your graduate program.

Name _____ Undergraduate School _____

Number and Street _____

City _____ State _____ Zip Code _____

UNIVERSITY OF KENTUCKY

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

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A Unique Program in AIR POLLUTION CONTROL

Kinetics and equilibria of atmospheric reactions

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Effects of pollutants on man, materials, and environs

Excellent, U.S.P.H.S. Traineeships available

At U.K.—a nine-man faculty, new laboratory and classroom facilities, a complete graduate curriculum, a variety of research topics . . .

Contact: Robert B. Grieves

Dep't of Chemical Engineering

University of Kentucky

Lexington, Kentucky 40506



DEPARTMENT OF
CHEMICAL ENGINEERING

UNIVERSITY OF MARYLAND

COLLEGE PARK, MARYLAND 20740

The Department offers graduate work in chemical, materials, and nuclear engineering leading to the M.S. and Ph.D. degrees. Some of the fields of specialization of the faculty are:

Chemical Engineering

Process Control Systems
Heat and Mass Transfer
Turbulent Transport
Solvent Extraction
Design and Cost Studies
Reaction Kinetics
Catalysis
Multiphase Flow
Process Dynamics
Computer Simulation

Biological and

Environmental Engineering

Aerosol Mechanics
Membrane Separations
Artificial Organs
Bioengineering
Environmental Health
Air Pollution Control

Nuclear Engineering

Nuclear Reactor Physics
Nuclear Reactor Design
Nuclear Reactor Operation
Radiation Induced Reactions
System Dynamics
Radiation Shielding
Radiation Engineering
Thermionics

Engineering Materials

Reaction of Solid Surfaces
Solid State Behavior
Composite Materials
Statistical Thermodynamics
Structure of Metallic Solutions

Applied Polymer Science

Polymer Physics
Graft Polymerization
Polymerization Kinetics
Non-Newtonian Flow

The general requirements are set forth in the Graduate Catalog. The chemical engineering program is designed for qualified bachelors chemical engineering students. The materials and nuclear engineering programs are open to qualified students holding bachelors degrees in engineering, the physical sciences, and mathematics.

Address inquiries to

Dean, Graduate School or Chairman Department of Chemical Engineering

**What are
YOU
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in a
GRADUATE
PROGRAM?**

THE UNIVERSITY OF MICHIGAN OFFERS

EXPERIENCE

The University of Michigan, Department of Chemical and Metallurgical Engineering, has operated graduate degree programs for over 50 years. We have awarded over 300 doctorates and 1000 master's degrees.

VARIED RESEARCH

The 35 faculty members work in all the traditional areas of research and also such fields as plasma reactions, process dynamics, catalyst structure, biochemical processes, electrochemistry, multi-phase systems, computer-assisted design, non-Newtonian fluids, and reservoir engineering.

CULTURAL ENVIRONMENT

Besides the usual campus activities the University and the Ann Arbor community offers the students scores of concerts by famous artists, lectures held throughout the year, plus the three drama series—all handy to campus. Ann Arbor is located in a river valley and is ideal for both winter and summer sports.

FINANCIAL ASSISTANCE

Most of our American and Canadian students receive financial assistance. Also, the University has excellent employment opportunities for student wives.

Write for information and a special book to:

**Prof. Rane L. Curl, Chairman of the Graduate Committee
Chemical Engineering Division
Department of Chemical and Metallurgical Engineering
The University of Michigan
Ann Arbor, Michigan 48104**



Department of Chemical Engineering

UNIVERSITY OF MISSOURI — ROLLA

ROLLA, MISSOURI 65401

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—Dr. J. L. Gaddy
- (b) Evaporation through non-Wettable Porous Membranes—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—Drs. M. E. Findley, and R. C. Waggoner
- (g) Transport Properties and Kinetics—Dr. O. K. Crosser
- (h) Thermodynamics, Vapor-Liquid Equilibrium—Dr. D. B. Manley



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



GRADUATE STUDY
IN
CHEMICAL ENGINEERING
AT THE
UNIVERSITY OF NEBRASKA

PROGRAMS LEADING TO THE
M.S. AND PH.D. DEGREES
WITH RESEARCH IN

Biochemical Engineering
Computer Applications
Crystallization
Desalination
Food Processing
Heat Transfer
Kinetics

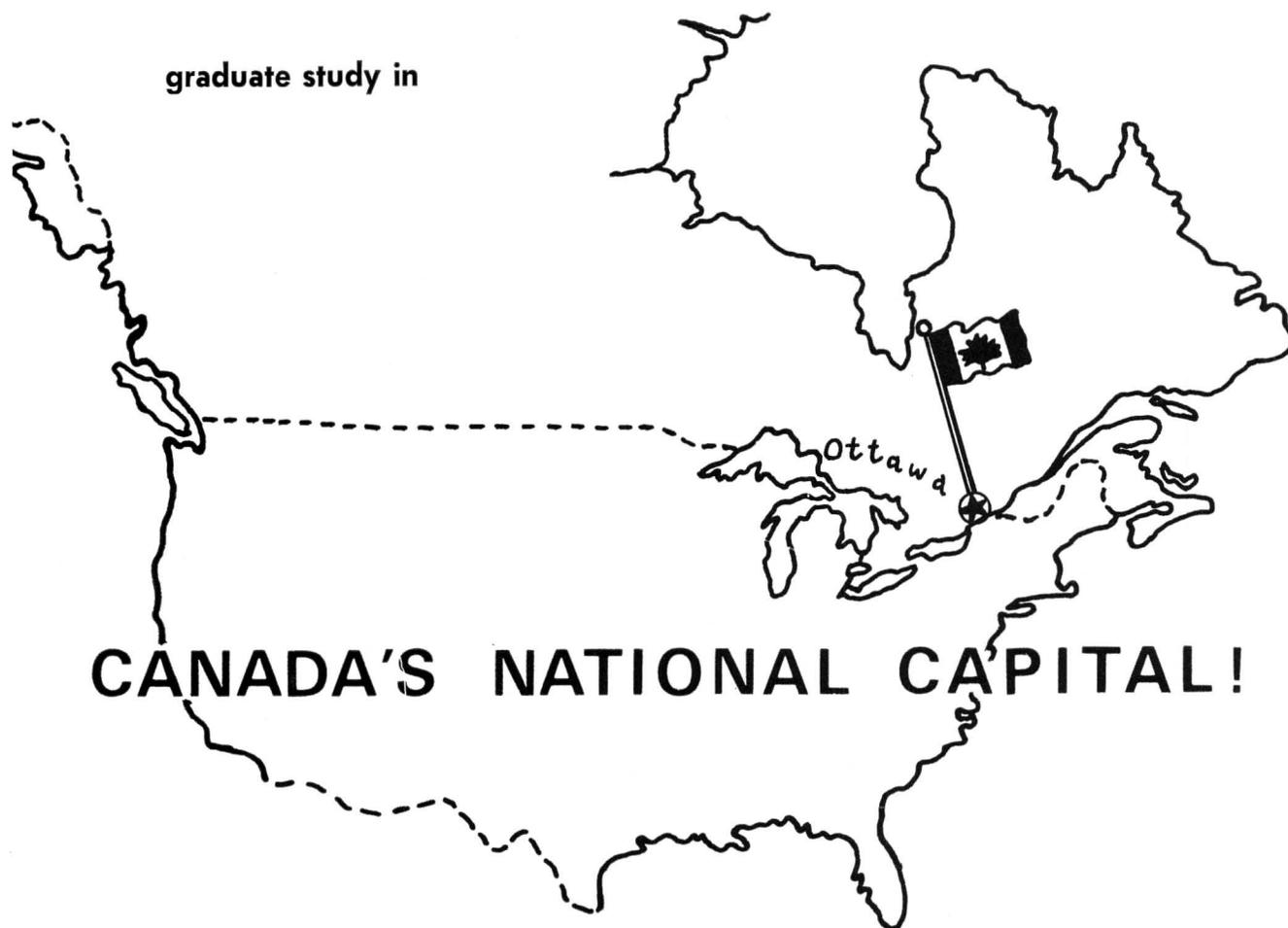
Laser Applications
Mass Transfer
Mixing
Polymerization
Thermodynamics
Ultrasonics
and other areas

FOR APPLICATIONS AND INFORMATION
ON AVAILABLE FINANCIAL ASSISTANCE

WRITE TO

Prof. J. H. Weber, *Chairman*
Department of Chemical Engineering
University of Nebraska
Lincoln, Nebraska 68508





THE UNIVERSITY OF OTTAWA offers a full program of studies and research leading to the masters and Ph.D. degrees in chemical engineering. Well equipped laboratories and modern facilities reside in a recently completed engineering complex. Extensive computing facilities, including an IBM 360/65, are used for course work and research. The staff includes seven full-time professors offering graduate courses and directing research. The graduate program has operated for fifteen years.

CURRENT RESEARCH

- Drag reduction phenomena in turbulent flow
- Viscoelastic effects in flow through porous media
- Membrane separations
- Phase equilibria at cryogenic temperature
- Foam separation of metallic ion pollutants
- Development of selective heterogeneous catalysts
- Mass transfer with reaction
- Polymerization kinetics
- Computer control of chemical processes
- Bio-oxidation in water recovery

THE UNIVERSITY

The University of Ottawa offers instruction in engineering, science, social sciences, and the humanities to a coeducational student body numbering about 7,000. It is situated in Canada's capital, Ottawa, whose population is 400,000.

FINANCES

Fellowships, Teaching Assistantships, and Research Assistantships are available. Minimum graduate student support is \$3,000, and increments are made annually.

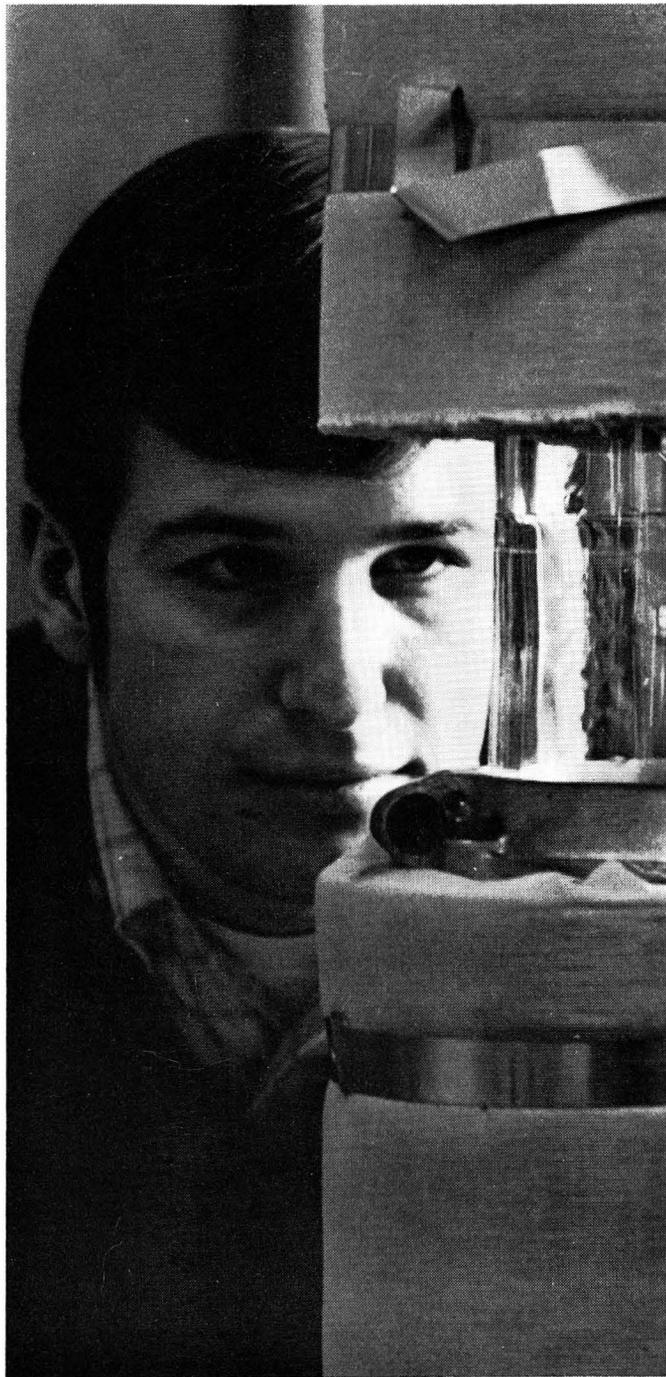
CULTURE AND RECREATION

The bilingualism of Canada is reflected in the cultural offerings of Ottawa, featuring renowned performers in the English and French languages. World famous orchestras, ballet companies, and art exhibitions appear regularly in the National Arts Center.

Ample opportunities for outdoor recreation exist in the Ottawa environs. Several skiing facilities are within 20 miles of the campus.

FURTHER INFORMATION: Address inquiries to: Chairman, Department of Chemical Engineering, University of Ottawa, OTTAWA 2, Canada.

LOOKING



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Petroleum Research

Unit Processes

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Catalysis and Applied Chemistry

Air Environment

Bio-Engineering

Nuclear Technology

Transport Properties

Lubrication and Rheology

And Other Areas

WRITE TO

Prof. Lee C. Eagleton, Head
160 Chemical Engineering Building
The Pennsylvania State University
University Park, Pa. 16802

GRADUATE STUDY IN CHEMICAL AND PETROLEUM ENGINEERING

University of Pittsburgh
M.S. and Ph.D. Degrees



PROGRAM

Chemical and Petroleum Engineering is one of six School of Engineering departments which offer graduate degrees. Interdisciplinary programs with other engineering departments and with other PITT schools and divisions such as Public Health, Natural Sciences and Medicine are encouraged.

Courses begin in September, January and April; graduate students may enter in any term.

FACULTY AND FIELDS OF RESEARCH

IN CHEMICAL ENGINEERING

Dr. Charles S. Beroes	Gas Dynamics, Process Design & Optimization, Unsteady State Heat Transmission
Dr. Alan J. Brainard	Thermodynamics, Mass Transfer
Dr. George D. Byrne	Applied Mathematics
Dr. Shiao-Hung Chiang	Mass Transfer, Interfacial Phenomena
Dr. Morton Corn	Air Pollution
Dr. James Coull	Chemical Kinetics, Catalysis, Polymers, Thermogravimetal Separation
Dr. Benjamin Gal-Or	Transport Phenomena, Relativistic Thermodynamics
Dr. Harold E. Hoelscher	Reaction Kinetics, Interfacial Phenomena
Dr. George E. Klinzing	Fluid Dynamics, Transport Phenomena
Dr. Chung-Chiun Liu	Electrochemical Engineering
Dr. Yatish T. Shah	Transport Phenomena
Dr. Edward B. Stuart	Thermodynamics, Adsorption
Dr. John W. Tierney	Process Dynamics, Equilibrium Stage Calculations
Dr. Lemuel B. Wingard	Biomedical Engineering, Enzyme Catalysis

IN PETROLEUM ENGINEERING

Dr. Paul F. Fulton	Multiphase Flow in Porous Media, Wettability
Prof. James H. Hartsock	Computer Applications to Unsteady State Flow
Dr. Joseph J. Taber	Interfacial and Surface Phenomena, Miscible Displacement

FINANCIAL ASSISTANCE

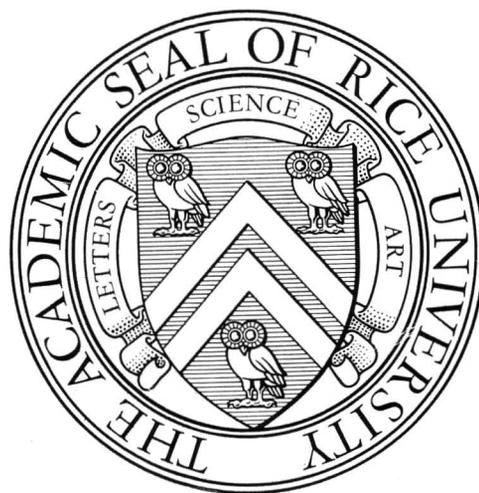
Graduate assistantships, research assistantships, fellowships and tuition scholarships are available to qualified students.

Financial support is provided by the University, industry, and various government agencies. Among sponsors of current research programs are Petroleum Research Fund, National Science Foundation, U.S. Department of Agriculture, National Aeronautics and Space Administration, and United States Steel Corporation.

For application forms and detailed information on FELLOWSHIPS, ASSISTANTSHIPS, and ACADEMIC AND RESEARCH PROGRAMS, write to:

Graduate Coordinator
Chemical and Petroleum
Engineering Department
601 Engineering Hall
University of Pittsburgh
Pittsburgh, Pennsylvania 15213

GRADUATE STUDY IN CHEMICAL ENGINEERING AT RICE UNIVERSITY



The Department

Rated by the American Council of Education among the top 15 Chemical Engineering Departments in the U. S. It has:

- 35 graduate students
- 10 postdoctoral fellows and research associates
- 12 full-time faculty
- excellent laboratory and computer facilities.

The University

Full University with programs in health and social sciences and humanities, as well as engineering.

Excellent library with extensive holdings.

Attractive 300-acre campus with fine recreational facilities.

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 and Biomaterials

Degree Programs

M.S. and Ph.D. degrees offered in Chemical Engineering.

Interdisciplinary programs in Biomedical Engineering and Polymer Science.

FALL 1970

Faculty

- W W. Akers, Ph.D., U. of Texas, Professor
- C. D. Armeniades, Ph.D., C.W.R.U., Asst. Prof.
- S. H. Davis, Jr., Sc.D., M.I.T., Professor
- H. A. Deans, Ph.D., Rice U., Professor
- D. C. Dyson, Ph.D., U. of London, Asso. Professor
- G. D. Fisher, Ph.D., Johns Hopkins U., Asst. Prof.
- J. D. Hellums, Ph.D., U. of Texas, Professor
- J. W. Hightower, Ph.D., Johns Hopkins U., Prof.
- R. Jackson, D.Sc., U. of Edinburgh, Professor
- R. Kobayashi, Ph.D., U. of Michigan, Professor
- T. W. Leland, Jr., Ph.D., U. of Michigan, Prof.
- L. V. McIntire, Ph.D., Princeton U., Asst. Prof.

Financial Support

Fellowships and assistantships are available with tuition remission and stipends competitive with other major universities.

Graduate assistants' duties require less than 6 hours per week and allow full-time study load.

Applications

Address letters of inquiry to:

Dr. C. D. Armeniades, Assistant Professor
Department of Chemical Engineering
Rice University
Houston, Texas 77001

**AT THE UNIVERSITY OF TENNESSEE
GRADUATE STUDY IN CHEMICAL
& METALLURGICAL ENGINEERING**

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 systems and design, or it may serve as preparation for more advanced work leading to the Doctorate.



FACULTY AND RESEARCH INTERESTS—William T. Becker, Ph.D., Illinois, Mechanical Properties and Deformation; Donald C. Bogue, Ph.D., Delaware, Rheology, Polymer Science and Engineering; Charlie R. Brooks, Ph.D., Tennessee, Electron Microscopy, Thermodynamics; Oran L. Culberson, Ph.D., Texas, Operations Research, Process Design; George C. Frazier, Jr., D. Eng., Johns Hopkins, Kinetics and Combustion, Transfer with Reaction; Hsien-Wen Hsu, Ph.D., Wisconsin, Thermodynamics, Transport Phenomena, Optimization; Homer F. Johnson, D. Eng., Yale, (Department Head), Mass Transfer, Interface Phenomena; Stanley H. Jury, Ph.D., Cincinnati, Sorption Kinetics, Hygrometry, Information Operations; William J. Kooyman, Ph.D., Johns Hopkins, Reaction Kinetics in Flow Systems; Carl D. Lundin, Ph.D., Rensselaer, Physical Metallurgy, Welding; Charles F. Moore, Ph.D., L.S.U., Process Control and Dynamics; Ben F. Oliver, Ph.D., Pennsylvania State University, (Professor-in-charge of Metallurgical Engineering), Solidification, High Purity Metals; Joseph J. Perona, Ph.D., Northwestern, Mass Transfer and Kinetics, Heat Transfer; Joseph E. Spruiell, Ph.D., Tennessee, X-ray Diffraction, Electron Microscopy, Polymer Science and Engineering; E. Eugene Stansbury, Ph. D., Cincinnati, Thermodynamics Kinetics of Phase Deformation, Corrosion; James L. White, Ph.D., Delaware, Polymer Science and Engineering, Rheology, Separation Processes.

REGULAR PART-TIME—Lloyd G. Alexander, Ph.D., Purdue, Fluid Flow, Heat Transfer; Bernard S. Borie, Ph.D., M.I.T., X-ray Diffraction; Albert H. Cooper, Ph.D., Michigan State, Process Design, Economics; Kenneth H. McCorkle, Ph.D., Tennessee, Colloidal Systems; Carl J. McHargue, Ph.D., Kentucky, Physical Metallurgy; Roy A. Vandermeer, Ph.D., Illinois Institute of Technology, Physical Metallurgy, Jack S. Watson, Ph.D., Tennessee, Fluid Mechanics.

LABORATORIES AND SHOPS—Analog computer (Expanded EAI, PACE 221R) and digital computer (DEC, PDP 15/20 with analog interface), High-speed automatic frost point hygrometer, Mass and heat transfer in porous media, Polymer rheology (Weissenberg rheogoniometer, Instron rheological tester, roll mill, extruder). Polymer characterization (gel permeation chromatograph, osmometer), Mass spectograph, Continuous zone centrifuge, Process dynamics, X-ray diffraction (including single crystal diffuse scattering analysis), Electron microscopes (Philips EM75 EM300), Calorimetry (25-1000°C), Electrical resistivity measurements for studies of structural and phase changes, Single crystal preparation facilities, Mechanical fabrication and testing, (metallograph, optical microscopes and melting, etc.), High purity materials preparation, Electronic and mechanical shops staffed by thirteen full-time technicians and craftsmen.

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COSTS TO STUDENTS—Full-time Tennessee residents pay \$105 per quarter maintenance fee; out-of-state students pay an additional tuition of \$205 per quarter; combined room-and-board arrangements are available at \$305 per quarter. One- and two-bedroom married student apartments rent from \$60 to \$110 per month unfurnished, approximately \$15 higher furnished. Privately operated apartments are available to single or married graduate students at equivalent and higher rates.

STUDENT BODY—About 20,000 students are enrolled at the Knoxville campus. In the College of Engineering there are approximately 2200 undergraduate and 300 resident graduate students.

KNOXVILLE AND SURROUNDINGS—Knoxville, with a population near 200,000, is the trade and industrial center of East Tennessee. The University is located about five blocks from the downtown business area. In the nearby Auditorium-Coliseum, Broadway plays, musical and dramatic artists, and other entertainment events are regularly scheduled. Knoxville has a number of points of historical interest, a theater-in-the-round, 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.

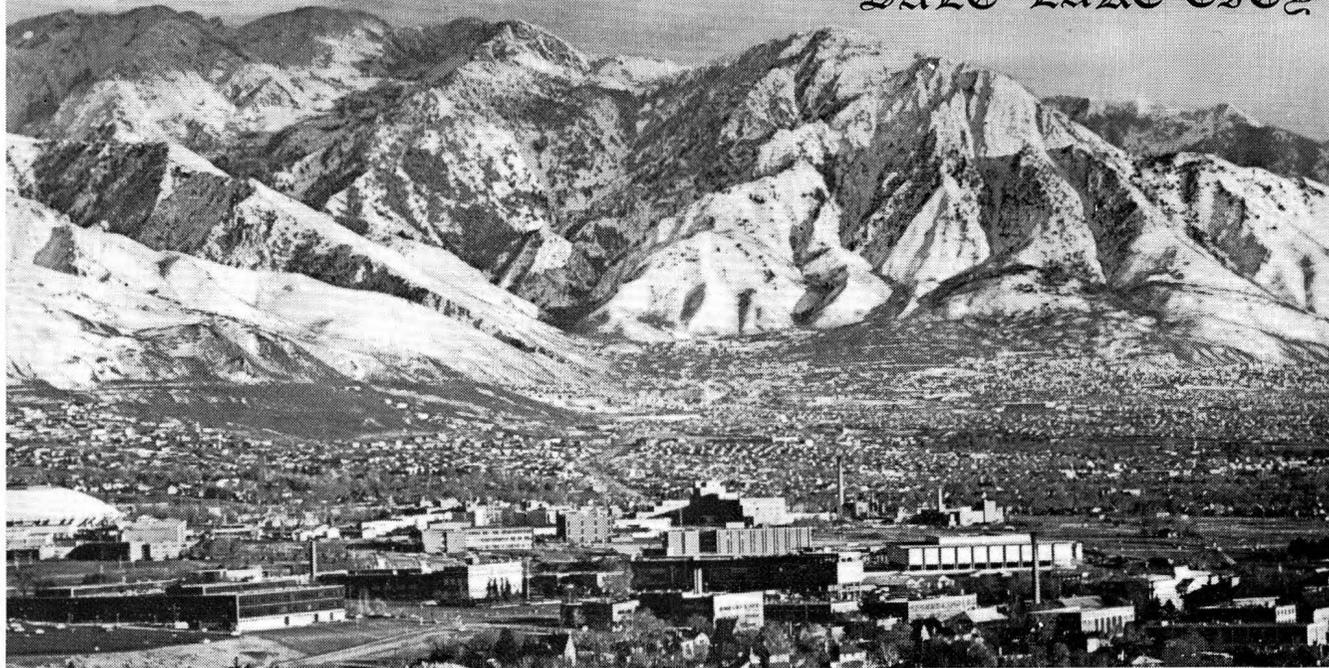
ABOUT UT—Founded in 1794 as Blount College, the University has grown to a large multi-campus, multi-purpose system of higher education covering the entire state. Graduate programs in science and engineering centered at the Knoxville campus have developed to major size and strength over the past 25 years stimulated by cooperation developed between the atomic energy facilities and the University.

WRITE: Department of Chemical and Metallurgical Engineering
The University of Tennessee
Knoxville, Tennessee 37916

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The Department of Chemical Engineering offers a full program of graduate courses and research and design projects leading to the Master of Engineering, Master of Science, and Doctor of Philosophy degrees. Eight faculty members, all of whom have had extensive industrial experience and have earned national and international reputations in their fields, direct research in a wide variety of chemical-engineering and related areas. Strong supporting departments in mathematics and the physical sciences; the Rate Processes Institute, directed by Dr. Henry Eyring; and the divisions and institutes in which chemical-engineering staff participate--the Biomedical Engineering Institute, together with the Artificial Organs Division, headed by Dr. Willem J. Kolff, and the research-oriented, on-campus University Hospital; the Environmental Engineering Division and the Center for Environmental Biology; the Fluid Mechanics Division; and the Engineering Systems Division--all strengthen and add variety and relevance to graduate study and research programs. Modern, well-equipped laboratories and adjacent computer facilities (Univac 1108) support research programs in all areas. Teaching emphasis is upon fundamental engineering principles and the development of ability in analysis, synthesis, insight, judgment, and the creative solution of pressing human problems. The University maintains housing accommodations for both single and married students, and there are many reasonably priced apartments within walking distance of the campus. Located at the foot of the Wasatch Mountains in the geographic, economic, and cultural center of the Intermountain West, Salt Lake has long been noted for its superb scenery, outdoor recreational facilities, natural resources, and hospitality.

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E.B. CHRISTIANSEN, Prof. and Chm.; PhD, U of Michigan. Newtonian and non-Newtonian momentum and energy transport, particle dynamics, biological transport processes.

A.D. BAER, Prof.; PhD, U of Utah. Heat transfer, fluid dynamics, process control, combustion.

R.H. BOYD, Prof.; PhD, MIT. Polymer and materials science, chemical thermodynamics.

N.W. RYAN, Prof.; ScD, MIT. Combustion, high-temperature reactions, gas dynamics, propulsion.

D.L. SALT, Prof.; PhD, U of Delaware. Diffusional operations, fluid and particle dynamics, separation processes.

J.D. SEADER, Prof.; PhD, U of Wisconsin. Coupled chemical-reaction kinetics, momentum, energy, and mass transport; ablation; polymer flammability; systems; design.

N.H. de NEVERS, Assoc. Prof. and Assoc. Dean; PhD, U of Michigan. Thermodynamics, multi-phase flow, chromatographic transport.

A.L. TYLER, Assist. Prof.; PhD, U of Utah. Chemical-reaction kinetics, particle dynamics, vapor-phase reactions, solid-state diffusion.

Assistance & Application

The Department offers NDEA Fellowships, NSF and Environmental-Pollution Traineeships, and a variety of research, design, and teaching assistantships to qualified applicants. Application materials and further information may be obtained by sending the coupon below to:

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Dr. Richard W. Hanks
234 ELB, Chemical Engineering
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B. J. McCoy:	Molecular Theory, Transport Processes
J. M. Smith:	Water Pollution, Reaction Design
S. Whitaker:	Fluid Mechanics, Interfacial Phenomena

Write To:

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



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Barlage, W. B., Ph.D., N. C. State—Transfer Processes in Non-Newtonian Fluids
Beckwith, W. F., Ph.D., Iowa State—Transport Phenomena
Bruley, D. F., Ph.D., U. Tennessee—Process Dynamics, Bio-medical Engineering
Hall, J. W., Ph.D., U. Texas—Chemical Kinetics, Catalysis, Design
Harshman, R. C., Ph.D., Ohio State—Chemical and Biological Kinetics, Design
Littlejohn, C. E., Ph.D., V.P.I.—Mass Transfer
Melsheimer, S S., Ph.D. Tulane—Process Dynamics, Applied Mathematics
Mullins, J. C., Ph.D., Georgia Tech—Thermodynamics, Adsorption

FINANCIAL ASSISTANCE—Fellowships, Assistantships, Traineeships

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C. E. Littlejohn, Head
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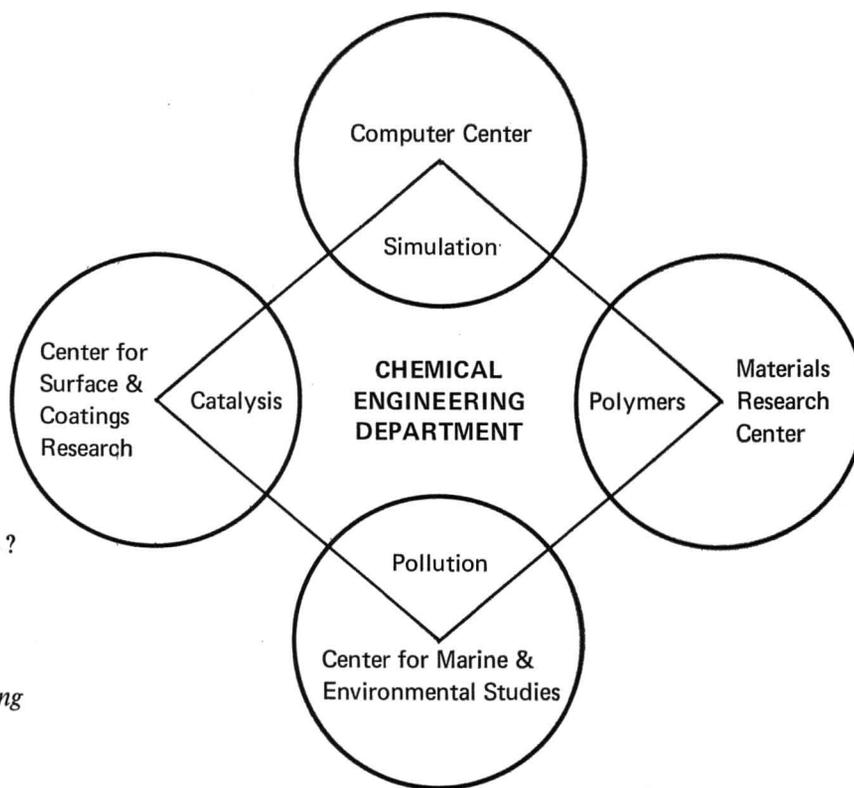
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Professor B. G. Kyle
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 Kansas State University
 Manhattan, Kansas 66502

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P. T. Eubank, Gas Phase Thermodynamics
D. T. Hanson, Bio-Engineering
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DR. A. RUSHTON

Department of Chemical Engineering
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TO DEPARTMENT CHAIRMEN

The staff of CEE wishes to thank the 51 departments whose advertisements appear in this second graduate issue. We also appreciate the excellent response you gave to our request for names of prospective authors. We regret that, because of space limitations, we were not able to include some outstanding papers and that certain areas are not represented. In part our selection of papers was

based on a desire to complement this issue with that of 1969, for we hope that seniors interested in graduate school will read both issues. As indicated in our letter of September 1, we are sending automatically to each department at least sufficient free copies of this issue for 1/5 the number of bachelor's degrees reported in "ChE Faculties". Because of the large number of requests you made for extra copies for seniors and graduate students, we were forced to limit the number of these to the total number of bachelor's degrees your department reported. However if you have definite need for more copies than you received, we may be able to furnish these upon request.

During the three years CEE has been published at the University of Florida its support has been derived primarily from industrial advertisers and donors. Unfortunately that source of support is now decreasing rapidly—due to economic reasons. For example, while CEE's income from industrial sources was \$9,240 in 1969, it is expected to be only \$7,300 in 1970 and recent trends indicate that our industrial support in 1971 may be as low as \$2,000—or a drop of \$7,240. Since the bulk of our support has come from industrial sources, it will be more important than ever for departments and faculty members to assist us through bulk and individual subscriptions. We are very appreciative that we have had the support of 123 departments in 1970, and we like to urge you not only to continue your support in 1971, but also to see if it can be increased by ordering additional copies, these may be used as follows:

- 1) One copy to each faculty member
- 2) One copy each to your engineering deans, department chairmen, and other university faculty.
- 3) One copy each to student chapter officers.
- 4) Extra copies for graduate students interested in teaching, for local high school counselors and chemistry teachers, and for AIChE local section officers.

Please keep in mind that payment for these bulk subscriptions (at \$4.00 each with \$25 minimum for 6 copies or fewer) may be made by any of the following means (or combination thereof): (1) Direct payment by check from departmental funds. (2) Payment by check after solicitation from the faculty of individual contributions and (3) Payment from university funds after being billed.

You may order your copies from Dr. R. B. Bennett, CEE Business Manager, Department of Chemical Engineering, University of Florida, Gainesville, Florida. 32601.

Ray Fahen, Editor

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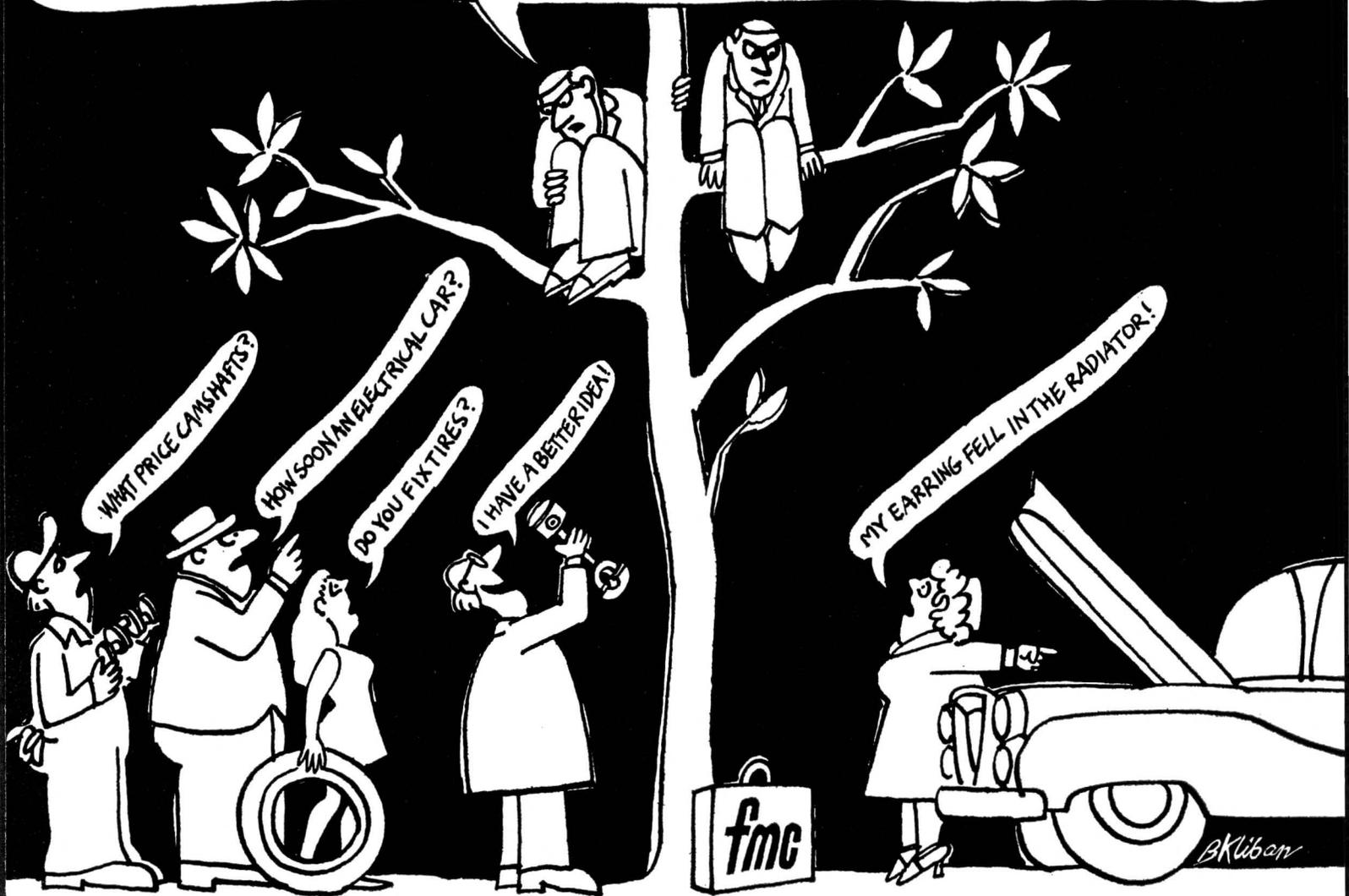
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