CEE

chemical engineering education

VOLUME XVI ○ NUMBER 3 • SUMMER 1982

ASEE

CHEMICAL ENGINEERING DIVISION OF AMERICAN SOCIETY FOR ENGINEERING EDUCATION

C. O. BENNETT
OF CONNECTICUT

· CHE AT YALE ·

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VOLUME XVI NUMBER 3 SUMMER 1982

FEATURES

DEPARTMENTS

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ChE educator

C. O. Bennett

OF CONNECTICUT

STUART M. CASE AND
ROBERT W. COUGHLIN
University of Connecticut
Storrs, CT 06268

C + O + B → Many Active Sites

That equation is not about carbon, oxygen and boron; it is about a man whose initials are COB, whose friends and acquaintances often call him CO and who does research on the catalytic chemistry of CO.

"He's a rare blend of humanist and scientist. If fate had rolled the dice a bit differently, he might have been equally productive as an English professor instead of as a chemical engineer."

These are the words of a professor of chemical engineering at a midwestern university talking about one of his former teachers, Carroll O. Bennett of the University of Connecticut. Another chemical engineering professor described Bennett as "one of the most liked chemical engineers in the country." Add to that the lasting influence of his co-authored textbook, "Momentum, Heat, and Mass Transfer," first published in 1962 and still a world-wide standard classroom and reference work, and it is no surprise that Bennett's selection for the 1980 Warren K. Lewis Award was greeted so enthusiastically.

For the modest, soft-spoken chemical engineering professor, the path to the AIChE's highest award for chemical engineering education is especially poignant. This is because it puts him directly in the footsteps of one of the great influential teachers in his own life, Yale chemical engineering professor, Barnett F. Dodge, who won the first Lewis Award back in 1963.

Because transient experiments must be purged of the influences of transport resistances, Bennett became an early designer of gradientless reactors, which were forerunners of the now well-known Berty reactor.

Bennett's path to the prize led him through a career that penetrated areas as diverse as meteorology and engineering design, and led to journeys on four continents. Along the way he became a gourmet, a lover of fine art and music, and fluent in four languages.

Born in New Britain, Connecticut's "hardware city," Bennett grew up as an only child. Even in high school, Bennett found he had an interest in chemistry, but also found himself drawn to the study of languages, doing well in the study of Latin, French, and German. Influenced by the reality of the depression, however, he continued his studies at Worcester Polytechnic Institute and by the end of his freshman year had chosen to study chemical engineering. After receiving his degree in an accelerated program in 1943, he entered the Army Air Corps.

Returning to Connecticut after the war, Bennett worked for a while as a metallurgist before deciding to continue studies in chemical engineering. Bennett spent three years at Yale, receiving his doctorate in 1950. At Dodge's suggestion, he did his thesis research in the area of high pressure thermodynamics. "I studied the compressibility of mixtures of hydrogen and nitrogen up to pressures of 3,000 atmospheres. It was rather interesting work, with a lot of mechanical technique involved." Yale, of course, was where J. Willard Gibbs had done much of his pioneering work on thermodynamics at the end of the 19th century, and his influence was still strong at Yale when Bennett was there.

At the same time, Bennett kept up his interest in French, taking courses in French literature with Henri Peyre, ". . . who is very well known to anybody who knows anything about French literature. I also went to lectures in art history by Vincent Sculley, who is another shining light at Yale," Bennett recalls. Both of these interests were to reemerge later and influence his career and life.

Bennett remembers Dodge "as a man of great intelligence with a very special personality. He was quite austere to students." He recalls the weekly meetings he had with Dodge to discuss his progress on his thesis; "I would go in there and sit down in the chair, and he would look at me and I was supposed to start telling him what I had done. He would ask a few questions. I was always afraid I would say something wrong. I don't know whether Dodge did this purposely or not, but it was very effective. I was always prepared for my weekly meetings." While Dodge seemed somewhat distant at the time, Bennett says he realized later that the professor "was a man of all sorts of human characteristics. Of course, one never realizes that about one's professors."

Even though doctoral research in chemical engineering was not at all common back in those Yale days, Bennett knew he would stick with chemical engineering rather than switch to chemistry. "I didn't want to become a chemist because I didn't want to stay in the lab," he says. "I wanted to do things on a bigger scale, and the scale-up process—going from the small scale you have in the laboratory to the large scale you have in a chemical plant—interested me." But Bennett did not immediately go out into the field and scale up chemical plants. Instead he went into teaching at Purdue.

"When you go into a career as a teacher in engineering, there are two parts to it," according to Bennett. "One is the engineering part, which emphasizes teaching undergraduates, so they can go out and practice engineering the way MD's go out and practice medicine. The other part of one's life in being a university teacher is doing research."

Add to that the lasting influence of his co-authored textbook, "Momentum, Heat, and Mass Transfer," . . . and it is no surprise that Bennett's selection for the 1980 Warren K. Lewis Award was greeted so enthusiastically.

Looking back on that era, Bennett comments that there were many engineering problems then for which the solutions were not as clear as they are now. "When I was just starting out in the '50's, it became clear that chemical engineers would probably become more interested in fundamental research which would be more similar to research done in physical chemistry than to research done in engineering." Thus he started his research with Prof. Dodge in the basic area of thermodynamics. While the work did not have an immediate practical application in view, it was related to the fact that Dodge, along with others, was interested in solving problems connected with synthesizing ammonia from nitrogen and hydrogen. Dodge wanted to find a way of running the process at high pressure and temperature, so that no catalyst would be needed. Ultimately, Dodge's high temperature and high pressure process proved uneconomic, and now Bennett's research pursues the opposite approach: exploring low pressure and low temperature reactions using catalysts. Bennett finished his work with Dodge in the summer of 1949, about the time he began to realize that teaching might be interesting.

After considering various teaching offers, Bennett selected Purdue University where he started teaching thermodynamics, sharing the course with Prof. Joe M. Smith. Smith had just finished his book on the subject, and was even then a well-known teacher and researcher in chemical engineering. Smith had studied with Warren K. Lewis at MIT and had picked up Lewis' Socratic method of teaching.

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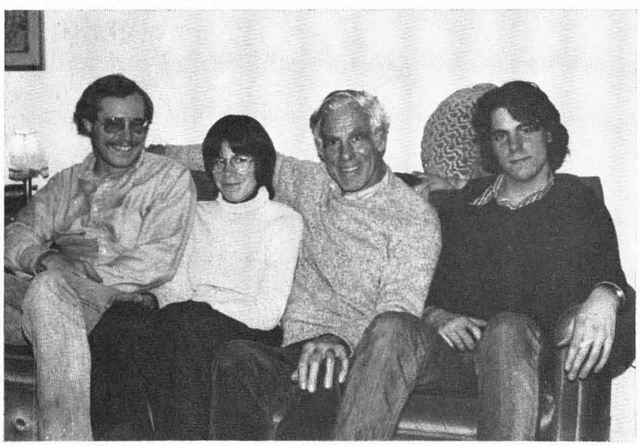
A year later another young instructor, Jack Myers, came from Michigan to join the Purdue faculty. Myers eventually became Bennett's co-author on the now-famous textbook. Bennett and Myers started thinking about the book in the mid to late '50s, began it about 1959, and published it in 1962, after Bennett had left Purdue for a stint in private industry. The book represented a new viewpoint on what the profession was really about.

In the old days, Bennett explains, engineers were associated with specific industries. Thus, there were sugar engineers, petroleum engineers, sulfuric acid engineers, and so on. Then, Lewis and Walker and others at MIT began to develop the idea of organizing chemical engineering in terms of "unit operations." These operations, such as distillation, extraction, absorption, and others,



CO relaxing with his children Edward, Elizabeth and Jonathan, after a skiing trip, in France.

were common to all sorts of chemical engineering processes. Thus, training a person in "unit operations," would enable him to go out and work in any one of the chemical industries.

That approach grew in strength and persuasiveness until it became increasingly clear that, behind the unit operations, there were really only a few basic divisions of the subject grouped around the concepts of heat, mass, and, momentum transfer. "We wanted to unify the unit operations which had previously unified the various different processes in chemical engineering, but to unify them as being manifestations of the principles of heat transfer, mass transfer, and momentum transfer," Bennett says.

At the same time, the computer revolution was just getting under way. "The first computers of any practicality began to be used in the '50s, and it became clear that it was practical to use more mathematics than you could previously," he notes. "You could solve certain differential equations or partial differential equations, or certain multi-component problems that previously would have been impractical to solve by hand because it would take too long, and you probably would make too many mistakes before you got through. The computer created an atmosphere where the fundamental approach became more attractive or more practical, and this, too, influenced the book."

While he was working on the book, and continuing his research on high pressures, mass transfer, and heat transfer, Bennett began to feel he would like to be a practicing engineer for a while. So in 1959 he left Purdue to join the Lummus Co. in New York as a development engineer. In the five years he was there, he worked hard to develop an independent design capability for the company, which previously had generated much of its business by using licensed processes developed by other companies.

"Dr. Bennett played a key role in establishing the research and development department at the Lummus Co., and the basic philosophies and approach which he established have been fundamental to the growth of this effort," according to a senior vice president at CE-Lummus, who added, "His spirit of free investigation and the practical application of fundamentals have contributed to the development and commercialization of a number of important processes." A former vice president for research and development at CE-Lummus noted that Bennett's association with Lummus was mutually beneficial and stated, "The Lummus Co. benefited in the early adoption of computer calculation techniques for chemical engineering design. Professor Bennett benefited in knowing how industry performs its work and what industry needs. No doubt such a combination has helped him to inspire his students and colleagues to high achievement."

Bennett's years at Lummus confirmed his belief that he was on the right track in returning to fundamentals as the basis of teaching chemical engineering. "It convinced me that a person who is intelligent and knows fundamental principles can go right in and compete with people who are experienced engineers, and who perhaps know how to do certain things, but don't remember or never

CO and his wife, Jean, on a night out in Storrs.

had the fundamental principles, so that their adaptability and flexibility are limited," he observes. "When improvements come along, or new processes or new situations develop, often the people with rusty fundamentals are not able to cope with them and design something suitable." He adds, too, that his teaching has been enhanced by the practical examples he can draw from his industrial experience, and he includes such problems in his lectures, his exams, and in his book.

It was from Lummus that Bennett came back to education, to the University of Connecticut, in 1964. And it was at UConn that Bennett's interest began to shift into the design of chemical reactors and heterogeneous catalysis. The field was not entirely new to Bennett, since some of his work at Lummus involved catalytic reactions, and many industrial processes are based on catalysts. "Nevertheless, catalysis was always thought of as a sort of black art and there seemed to be a lot of room for increased understanding. It seemed to be a good thing to study," Bennett reflected.

Bennett's elucidation and advocacy of the transient method for catalytic studies has helped to dispel some of the blackness of the catalytic art. This approach allows simple experimentation to shed light on the rich complexity of even the simplest catalytic reactions.

Following pioneering experiments by Wagner in 1938 and further work by Tamaru in 1963, Bennett laid out a quantitative framework in 1967 [AIChE Journal *13*, 890 (1967)]. Later Kobayashi and Kobayashi and Yang et al. implemented this approach, thereby bringing to full fruition the earlier emphasis by Wagner and Tamaru on measuring adsorption during catalysis.

Although transient experiments have long been applied in other fields, only within about the last 10 years have they found wide acceptance in heterogeneous catalysis. As recently as 1975, chemical engineers modelled reactors using steady-state rate expressions rather than models based on elementary steps and their individual rates which can change in response to changing conditions during transients.

Because transient experiments must be purged of the influences of transport resistances, Bennett became an early designer of gradientless reactors, which were forerunners of the now well-known Berty reactor. Later, Bennett applied transient methods to the study of Fischer-Tropsch catalysis and his current research work is largely in this area.

In addition to teaching and research, Bennett also served as acting department chairman on several occasions, but it was not his first love, and he was always happy to return to teaching and research. While teaching has its drawbacks for

Bennett's years at Lummus confirmed his belief that he was on the right track in returning to fundamentals as the basis of teaching chemical engineering.

Bennett (especially tasks like grading exams), it still is one of the best parts of the job for him. "Teachers should teach people," he believes. "I suppose I enjoy the opportunity to make something clear. When I can describe something in such a way that it is comprehensible maybe I can remember the first time I looked at it, and I too, thought, that it was incomprehensible."

Bennett teaches three undergraduate courses and one graduate course at UConn. One of these is a required 40-student section of the junior-year course in transfer operations. He also teaches advanced courses in transfer operations in the fall

Continued on page 144.

ChE department

CHE AT YALE

CHARLES A. WALKER
Yale University
New Haven, CT 06520

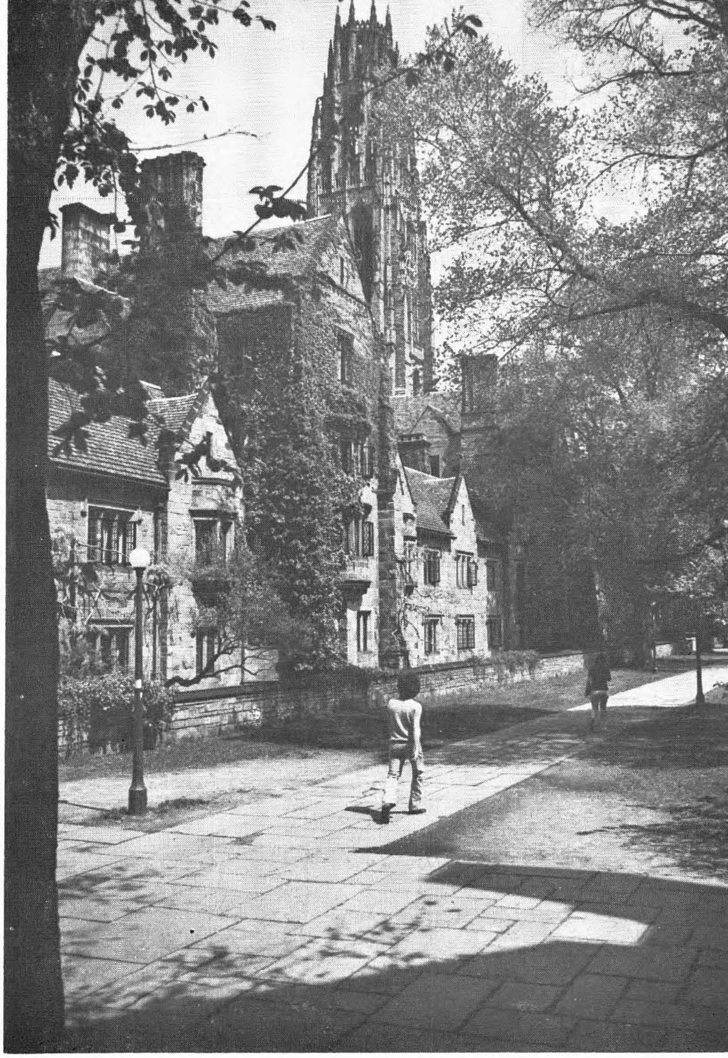


Photo by William K. Sacco

ALTHOUGH AN UNDERGRADUATE program in Industrial and Engineering Chemistry was offered in earlier years, a program in Chemical Engineering was first offered at Yale in 1922-23, and it was heralded as follows in the Report of the President for that year:

> **Professor Harry Alfred Curtis has been called to the chair of Chemical Engineering, for which we have provided admirable quarters in the new Sterling Chemistry Laboratory. . . . We shall look forward to the development of the new Department under his charge in the most hopeful spirit.**

Professor Curtis served as Chairman until 1931 and then left Yale to continue a distinguished career as director of research for a major oil company and later as Dean of Engineering at the University of Missouri and a member of the Board of Governors of the Tennessee Valley Authority. Before leaving, however, he had provided well for a successor in the person of Barnett F. Dodge, who came to Yale in 1925 and served as chairman from 1931 until his retirement in 1964. Professor Dodge's classic book on chemical engineering thermodynamics reflected his research interests in cryogenic engineering and phase equilibrium and chemical equilibrium at high pressures. Others who have served on the fulltime faculty in chemical engineering at Yale, in the order of the dates of their first appointments, and with the names of current faculty members in bold face type, are Clifford C. Furnas, Melvin C. Molstad, Roger H. Newton, Harold E. Graves, Winford B. Johnson, R. Harding Bliss, James A. Johnston, E. E. Lindsey, Jr., **Charles A. Walker**, Raymond W. Southworth, Homer F. Johnson, Dinwiddie C. Reams, Randolph H. Bretton, Shen-Wu Wan, John A. Tallmadge, Jr., Joshua Dranoff, John B. Butt, Colin McGreavy, Lawrence H. Shendalman, Reiji Mezaki, **John B. Fenn**, James B. Anderson, **Gary L. Haller**, **Daniel E. Rosner**, William N. Delgass, **Csaba Horvath**, **Paul C. Nordine**, Jimmie Q. Searcy, Constantinos G. Vayenas, **Bret L. Halpern**, and **Subbarao B. Ryali.** Comments on the contributions of each of the former faculty members are precluded by space considerations, but Harding Bliss's service as the first editor of *AIChE Journal* and the fact that the first course in computer programming at Yale was taught by a chemical engineer, Raymond W. Southworth, deserve to be mentioned. Research interests of current faculty members will be discussed later in this article.

. . . at Yale a unique aspect is the fact that chemical engineering students necessarily pursue their studies in close association with students and faculty members in many disciplines, including those in . . . social sciences and liberal arts.

Until 1962 chemical engineering activities at Yale were the responsibility of the Department of Chemical Engineering in the School of Engineering. In that year Yale embarked on an experiment in education by combining all engineering activities in a Department of Engineering and Applied Science in the Faculty of Arts and Sciences. While this experiment was successful in encouraging interdisciplinary teaching and research, the range of faculty interests was so broad as to make agreement on educational philosophy and faculty appointments difficult to achieve. In the spring of 1981 the faculty and administration judged that these difficulties were significant enough to justify a return to smaller, more homogeneous units, including a Department of Chemical Engineering.

During the years 1962-1981 chemical engineering activities continued under the direction of a faculty that varied in size from seven to ten members. During some of these years there were very few undergraduate students majoring in chemical engineering, and much of our effort was devoted to the graduate program and research. In more recent years undergraduate interest in chemical engineering has increased, as it has at other institutions, and the undergraduate program is again attracting reasonable numbers of students.

Thus, while we might appear to be a "new" department of chemical engineering, we are in fact a part of a continuing development of our discipline at Yale.

THE UNDERGRADUATE PROGRAM

THE UNDERGRADUATE CURRICULUM in chemical engineering at Yale is conventional in many respects and includes courses in the following subjects: introductory thermodynamics; conservation of mass and energy; chemical engineering thermodynamics; fluid mechanics; mass, energy, and momentum transport processes; chemical kinetics and chemical reactors; separation processes; chemical engineering laboratory; and chemical engineering process design, as well as options in biochemical engineering, environmental chemical engineering, and research projects.

The teaching of most of these subjects at Yale is not significantly different from the way they are taught in other universities and colleges. Each of us feels, of course, as do all educators worthy of the name, that he has developed an optimum method for teaching his subject or that at least he is now in position to teach it in optimum fashion *next year*. There seems to be little point, therefore, in outlining our approach to each of these courses, but two courses deserve special mention. Our course in chemical engineering process design is taught, quite successfully, by engineers from Olin Corporation. Dr. Herbert Grove, David Doonan, Joseph Levitzky, and Howard Martin have participated in teaching this course and have added significantly to the education of our students. We are grateful for their considerable efforts. Research projects can be taken for credit at any time in a student's undergraduate years. Each student is affiliated with one of several research groups and assigned a problem related to the ongoing research effort. Almost every chemical engineering student takes at least one semester of research, usually in the junior or senior year, and a few continue for two or more semesters and have their names appear on research publications.

Thus, while we might appear to be a "new" department of chemical engineering, we are in fact a part of a continuing development of our discipline at Yale.

The general requirements for graduation from Yale College include a total of 36 term courses, 12 of which must be outside the area of the major. Thus chemical engineering students must take 12 term courses in disciplines other than mathematics, science, and engineering, a considerably heavier requirement of humanities courses than is typical for engineering students at other institutions. We observe that some of our students use these 12 courses to explore several disciplines, such as literature, history, economics, philosophy, and languages. Others satisfy a set of distributional guidelines and then use the remaining courses to concentrate in one discipline. One student, for example, was able to arrange her courses so that she satisfied requirements for majors in both chemical engineering and English literature. Another satisfied requirements for majors in chemical engineering and economics. The breadth of education that results from meeting this requirement is an important and desirable feature of the curriculum.

Recognizing the diversity of interests of students, we offer undergraduate degrees in chemical engineering at three levels of intensity. For those who plan to enter the profession, a B.S. in Chemical Engineering, requiring a total of 40 term courses and carefully structured courses in chemical engineering, is available. For those interested in chemical engineering but desiring to take more courses in other disciplines, a B.S. in Engineering Science (Chemical), requiring a total of 36 term courses and fewer courses in chemical engineering, is offered. For students planning on business school, law school, or medical school, a still less intensive B.A. in Engineering Sciences (Chemical) degree is offered. Most of our students take one of the B.S. programs and, after graduation, more than half go directly to industry and others go to graduate school in chemical engineering or to schools of business, law, or medicine. Class sizes are small but growing; in the past few years we have awarded 10-12 undergraduate degrees each year.

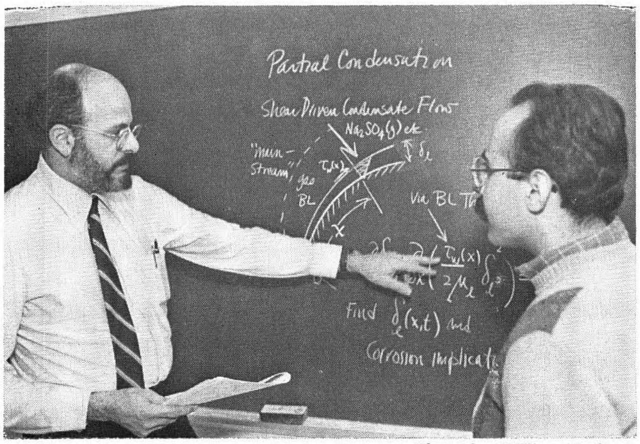


Photo by William K. Sacco

Dan Rosner at the blackboard with Suleyman Gokoglu.

In these *Chemical Engineering Education* articles about education at the variety of types of institutions that are the hallmark and the strength of higher education in the United States, readers deserve to learn what is unique about each institution as well as what they have in common. At the undergraduate level at Yale a unique aspect is the fact that chemical engineering students necessarily pursue their studies in close association with students and faculty members in many disciplines, including those in the natural sciences, the social sciences, and the liberal arts. This necessity is imposed in part by the fact that a large majority of undergraduates live on-campus in one of twelve residential colleges. These colleges are simply a basis for making dormitory life more attractive by providing a sense of belonging to well-identified units (Berkeley College, Silliman College, etc.) that are the centers of much of the social life of students, the intramural sports program, and numerous informal activities in the fine arts and the performing arts. The residential colleges are not organized by disciplines; in fact, considerable effort is expended in insuring that each college includes students with varied academic and extracurricular interests. Faculty members are also associated with these units, a few as residents, a few as occupants of offices in the colleges, a few as instructors in a limited number of general-interest seminars, and a larger number who take some of their meals in the college dining halls. The results of this system include a healthy mixing of students with varied interests and the encouragement of informal student-faculty interactions.

Thus chemical engineering students at Yale live in an atmosphere in which a majority of their classmates are majors in the humanities. This arrangement, the requirement of 12 term courses in the humanities, and the general educational value of studies in mathematics, science, and chemical engineering provide them with an opportunity to achieve a truly liberal education. As noted above, most of our graduates enter the chemical engineering profession, which we regard as among the most demanding and most satisfying of all professions. We are inclined to regard those students who go on to law, business, medicine, and other professions as tributes to the breadth of chemical engineering education rather than to bemoan the loss to our own profession.

THE GRADUATE PROGRAM AND RESEARCH

OUR CURRENT graduate program emphasizes research and the PhD degree. This is a reasonable allocation of resources in view of the fact that current faculty members are research-oriented and few in number. Topics for graduate courses are selected in part on the basis of their suitability as a preparation for research and they are taught by research-oriented faculty members. Current regular course offerings include chemical engineering thermodynamics, chemical reaction engineering, transport processes, separation processes, spectroscopic surface analysis, and electrochemistry fundamentals and applications. Courses in combustion science and technology, aerosol science and technology, biochemical separation processes, chromatography, heterogeneous catalysis, and other topics are also offered periodically. Because some of our graduate students enter with undergraduate majors in subjects other than chemical engineering, some upper-level undergraduate chemical engineering courses are used as mezzanine courses, i.e., graduate students can take them for credit by satisfying requirements in addition to those imposed on undergraduates.

At this time about 20 graduate students are in residence, most of whom are studying for the PhD degree.

Most of the graduate courses contain subject matter relevant to development and design as well as research. They are therefore appropriate for students interested in a terminal M.S. degree and careers in development and design, and we have a few such students. In order to provide these students with the opportunities that should be available to them, however, we recognize that we need to add courses in materials, computer-aided design of separation processes, chemical process control and optimization, and advanced chemical process design. We are currently discussing such possibilities, realizing that offering these topics would require additional personnel, some of whom might well be adjunct faculty members from industry.

Yale's experiment with a Department of Engineering and Applied Science was successful at the graduate level, and we have retained the title Engineering and Applied Science for our graduate program in collaboration with the Sections of Applied Mechanics (later to be Mechanical Engineering), Applied Physics, and Electrical Engineering. This arrangement provides some significant benefits. Courses common to these disciplines, including applied mathematics and experimental methods, are readily available to our students, as are courses in electronics, control systems, fluid mechanics, and a variety of other topics. Students are provided with greater flexibility in their choices of research topics, and interdepartmental barriers to collaborative research programs simply do not exist.

Course requirements for the PhD degree depend on a student's background and interests. A committee of three faculty members works with each student to select courses that serve to advance the student's knowledge of chemical engineering and to prepare him or her for research. Sometime during the first year or early in the second year each student begins the process of developing a research topic by enrolling for research with particular faculty members. The student is then expected to collaborate with one or more faculty members in developing a proposal for research on a topic for which funding and equipment are available or can be obtained.

Chemical engineering laboratories in Mason Laboratory and Becton Center are lively with the activities of faculty members, graduate students, undergraduates, and postdoctoral research associates. Expenditures on research from grants and contracts amount to about $800,000 for the 1981-82 academic year. The varied research interests of current faculty members are described briefly below.

John Fenn applies molecular beam methods to the study of a variety of scientific and technological problems. His well-equipped laboratory provides the means for studying the distribution of translational, vibrational, and rotational energies of molecules during and after such events as free jet expansion, collisions in the gas phase, and collisions with surfaces. The results are of interest in analyzing energy distributions in heterogeneous catalysis processes, monitoring of pollutants from internal combustion engines, understanding the infrared radiation characteristics of rocket exhaust plumes at high altitudes, and elucidating structures and reactions in messy

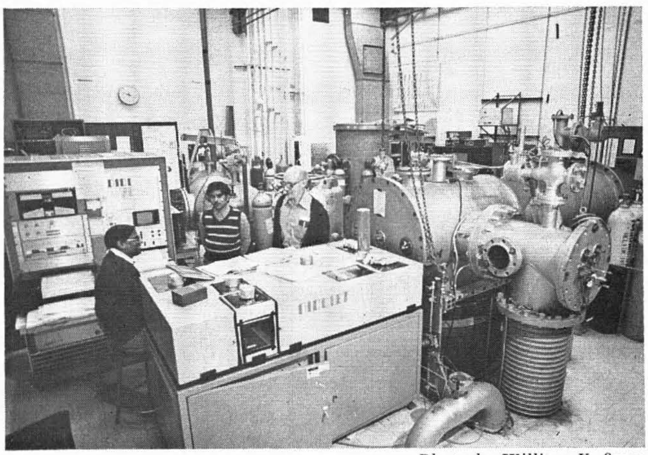


Photo by William K. Sacco

S. P. Venkatenshan, Subbarao Ryali, and John Fenn in the molecular beam laboratory.

mixtures such as biological fluids and coal-conversion process streams.

Dan Rosner is engaged in research on mass and energy transfer at fluid-solid and fluid-fluid interfaces. His laboratories are equipped for studies of nonequilibrium multiphase systems under extreme conditions (high temperatures, partially dissociated gases, particle-laden gases). Current studies include the deposition of soot, ash, and inorganic salts from combustion gases to heat exchange surfaces and turbine blades, surface-catalysed combustion, and the role of thermal diffusion in high-temperature processes.

Gary Haller's research interests are in surface chemistry and heterogeneous catalysis. Current studies include reactions of olefins on chromium oxide catalysts, analysis of binary alloy catalysts using X-ray, photoelectron, chemisorption, and reaction kinetics methods, and Fourier transform internal reflection infrared spectroscopy applied to metal-support interactions.

Csaba Horvath's research interests are in biotechnology with particular regard to biochemical separation processes and enzyme reactors. With Wayne R. Melander, Research Associate and Lecturer in the Department, he studies the fundamentals of chromatography and the thermodynamics of adsorption on non-polar surfaces. High performance liquid chromatography is used in fundamental studies of the interaction of biological substances with surfaces and the development of linear free energy relationships of technological significance. In collaboration with physicians at Yale and at Roswell Park Memorial Institute in Buffalo he is investigating the use of hollow fiber enzyme reactors in extracorporeal shunts in clinical applications. Other applications of enzyme reactors are in the production of precious biochemical substances and in food processing. He is also studying the design and optimization of high performance displacement chromatography, a potential industrial process.

Paul Nordine's research interests are in high-temperature heterogeneous reaction kinetics. He has developed techniques for jet levitation of solids and laser heating and applied them to studies of the preparation of crystals, reductive chlorination of metal oxides, and fluorine-resistant refractory materials.

Bret Halpern is also interested in the dynamics of chemical reactions catalyzed by solid surfaces. His studies on partitioning of chemical reaction energy within product molecules and energy dissipation in catalysts, monitoring of the deposition of hydrocarbons and carbon on metals, and oxidation of carbon at high temperatures complement John Fenn's interests. He is now engaged in expanding his interest in research on electrochemical processes.

Charles Walker has collaborated with social scientists during the past few years in studies of social and political aspects of problems in environment and energy. He has worked with the Department of Energy on technology assessment and is currently working with colleagues on a book about social and political problems in radioactive waste management.

COURSE REQUIREMENTS
B.S. IN CHEMICAL ENGINEERING,
YALE UNIVERSITY

	SEMESTERS
Calculus	3
Ordinary Differential Equations with Applications	1
Partial Differential Equations with Applications	1
Comprehensive General Chemistry (with laboratory)	2
Organic Chemistry	2
Physical Chemistry	2
Advanced General Physics (with laboratory)	2
Computer Science	1
Introductory Thermodynamics	1
Introduction to Chemical Engineering	1
Chemical Engineering Thermodynamics	1
Fluid Mechanics	1
Energy, Mass, and Momentum Transport Processes	1
Chemical Kinetics and Chemical Reactors	1
Separation Processes	1
Chemical Engineering Laboratory	1
Chemical Engineering Process Design	1
Chemical Engineering Projects	1
Technical electives in Engineering	2
Humanities courses	12

Subbarao Ryali uses molecular beam techniques to study energy exchange (translational, rotational, and vibrational relaxation processes) and energy transfer (translation to rotation and vibration) in gas-gas encounters under well-defined conditions. Other research interests include gas-surface interactions, nucleation and condensation, heat transfer, and combustion.

CLOSING COMMENT

THE COURSE of chemical engineering education is influenced by the institutional setting in which it occurs as well as by professional societies and the needs of employers of chemical engineers. There is, of course, a need for some degree of uniformity in the teaching of this discipline, but chemical engineering education can and should reflect the variety that is, as noted above, the hallmark and the strength of higher education in this country. As do other educators, we at Yale seek to develop courses, curricula, and research programs that are compatible with the long-range interests of the chemical engineering profession in its service to society and compatible with our own institutional setting. □

TWO GENTLEMEN FROM YALE

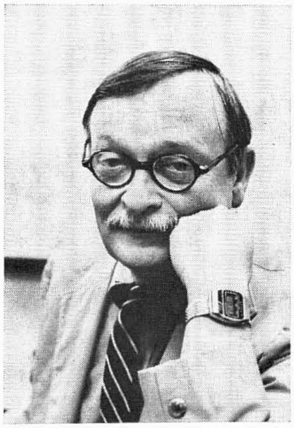
J. J. CARBERRY, Yale '57
University of Notre Dame
Notre Dame, IN 46556

R. Harding Bliss (1911-1971)

"Men," he remarked in the wake of one of our disastrous exam performances, "once again the Fourth Law is manifest—that Law in its original form states, you will recall, that there is always a parking spot on the other side of the street."

In an era which enshrines the illiterate, the "you know, man" cult of the witless who equate spasms with thought, he, R. Harding Bliss stands out, even in death, as a giant.

He taught from a wheelchair, a consequence of polio which was permanently visited upon him in the prime of his career. Yet that terrible infirmity failed to dampen his wit, charm, dedication to teaching and research. His was perhaps one of the first courses in Chemical Reaction Engineering to be offered in this country, if not in the world. It was a joy to participate in that offering, in spite of our all too frequent encounters with his Fourth Law. We did not "take" his course; rather we participated, for such was his zeal and humility that he wisely fashioned that course as an intellectual adventure marked by bilateral exchange—yet that classroom democracy never descended to the thought-barren level of a "rap" session. His was a classroom not a sandbox. It was a tough, demanding and therefore a most exciting arena. This was happily so because he was a tough, demanding and therefore a most exciting mentor. We loved him for those marvelous qualities enriched as they were by his wit and obvious love of his students. Such was that love that his departure from our midst ends not the grand affair. We love and are continually inspired by the memories. And I, for one, am seized by the intuitive vision of that grand gentleman of Yale now reminding Plato of the Fourth Law, to the everlasting joy of Dante and Bertrand Russell.



J. J. Carberry, Professor of Chemical Engineering at the University of Notre Dame since 1961, received his doctorate at Yale in 1957, following undergraduate work at Notre Dame ('50) for which G. I. Bill-sponsored undertaking he prepped at Brooklyn Technical High School and, at FDR's invitation, in WWII. He spent six years with the du Pont Company, a few years at Cambridge (NSF-Sr. Fellow—1966; Churchill Fellow—1979/1982); was Senior Fulbright Fellow (Italy 1974) and in spite of his Irish-American heritage was elected Fellow of the Royal Society of Arts in 1980. Thus his is now an Anglo-Irish inheritance.

In 1968 he received the Yale Engineering Association Award for the Advancement of Pure and Applied Sciences and in 1976 was recipient of the R. H. Wilhelm Award (AIChE) in Chemical Reaction Engineering. He is a member of the Advisory Council for Chemical Engineering at Princeton University, an appointment apparently inspired by Nassau Hall's fond expectation that Princeton may now have fond hopes of winning a football game against Yale.*

Author of the text "Chemical and Catalytic Reaction Engineering" (McGraw-Hill) and co-editor of "Catalysis Reviews—Science and Engineering" (M. Dekker, Inc.), Carberry is now contemplating co-authorship with Aris McPhearson Rutherford of a seminal opus "Isaac Newton's Indebtedness to the Gill Report—Historical contrasts in Mercury Poisoning."

*They did.

B. F. Dodge (1895-1972)

We were accustomed to setting our clocks not by radio nor the Bureau of Standards, but by Barney Dodge's arrival at Sterling Chemistry Lab, Yale. A more secure standard did not exist. His scholarly standards were as precise as his office hours, and as consistent. His method of teaching leaned heavily upon the "case method." While some might question that as a philosophy of teaching, none of us, in retrospect, can question the merits of Barney's "case method"; even the kineticists in our midst matured via Dodge's "Chemical Engineering Thermodynamics."

In this present age of devotion to "student-teacher evaluations," I doubt that Barney would fare very well—unless the students were required to render their assessments of him five or ten years after having suffered through his lectures. They might then, as I have, realize that their suffering was not in vain—indeed the fruits of our labors are great. For Barney imposed realities upon us while maintaining scholarly rigor with respect to the principles of chemical engineering; in particular, thermodynamics. And although his text on that subject is a classic, his research interests were catholic. Before absorption and simultaneous chemical reaction was formally acknowledged, B. F. Dodge directed seminal research in that area.

He was a precise and candid man, virtues hopefully still with us. Should we become devoid of these merits, it is solely because we suffer a paucity of great men such as B. F. Dodge. While we mourn his absence, his presence will not be forgotten nor will our love of him diminish.

I have no doubt that he arrived in the hereafter precisely on time and immediately proceeded to remind Plato of the first Three Laws to the everlasting joy of, amongst others, his great friend, R. Harding Bliss. □

ChE book reviews

FLUID FLOW AND HEAT TRANSFER
By Aksel L. Lydersen
John Wiley and Sons, 1979; 357 pages, $53.95 Hardbound, $22.50 Paperback

Reviewed by Kenneth J. Bell
Oklahoma State University

This book surveys a wide variety of subjects in fluid flow and heat transfer; in addition to the more obvious topics, there are chapters on Particle and Drop Mechanics, Liquid Filtration and Flotation, and Atomization, Dispersion, Homogenization, Crushing and Grinding. There is also a short chapter on Energy Economy. The general level of the treatment is at what might be termed the first professional level: these are the pieces of information and the equations that would be needed by a process engineer carrying out preliminary plant design. The need is to get reasonable answers to a wide variety of problems quickly, leaving the detailed design to be worked out later by specialists.

Little space is spent developing anything that might be considered a theoretical base if it does not contribute directly and immediately to problem solving. On the other hand, all working equations are there together with the necessary charts, tables, and nomograms to permit complete and consistent calculation of the answer required. There is also enough description of the various types of equipment to allow the non-specialist to make intelligent selections. Also, there are numerous completely worked-out examples (some of them of considerable complexity) which well illustrate the proper use of the design equations. Finally, the author includes a number of comments concerning points frequently overlooked or misunderstood by designers. If the book has a technical weakness, it is that the references that are given tend to be quite venerable so that anyone seeking additional information is going to be about ten years out of date.

So much for the technical content of the book. Where does it fit into the engineering curriculum? This is not so easy to answer. The book will not do for the introductory courses in fluid mechanics and heat transfer because of the almost total lack of presentation of fundamental material and the derivations of the working equations. It would perhaps be suitable for those few curricula which have advanced applied courses in these topics, but the faculty member would want to do a lot of updating with recent literature.

The book would be an excellent supporting volume for an undergraduate (or even a graduate) design course, but it cannot take the place of one of the books specifically oriented towards that topic (e.g., Peters and Timmerhaus). It is doubtful that it would be fair to expect a student to pay as much money as this for a purely subsidiary reference book, especially since much of the material in this book is to some extent covered in Perry's Handbook.

If it is hard to see where it fits into the chemical engineering curriculum, it is easy to recommend this book to the practicing engineer, especially one just beginning his career in process

Continued on page 144.

THE OSCILLATING SINK

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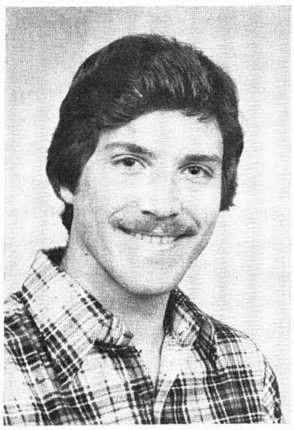
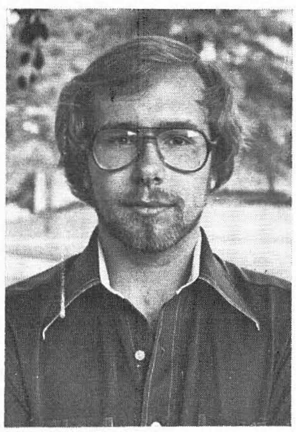
University Park, PA 16802

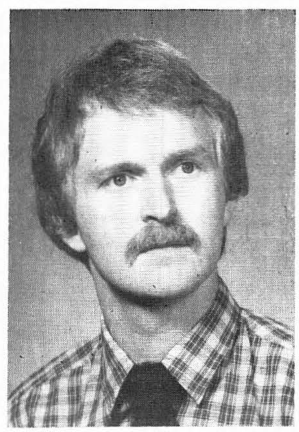
IN THE SUMMER OF 1978, while cleaning glassware in Room 3 of Fenske Laboratory, one of us (THL) observed that the level of water in the laboratory sink would periodically drop to a near empty level and then slowly climb back to a moderate height—all in the presence of what appeared to be a steady inflow of water from the faucet. These curious events, although memorable, were not accorded any particular significance until the following winter. At that time, THL attended a graduate Process Dynamics Course in which the subjects of Autonomous Oscillations and Bifurcations were presented in some detail. In this course, it was emphasized that systems with steady inputs (autonomous systems) could produce oscillatory outputs under appropriate conditions, and various analytical and computer exercises, mainly involving continuous stirred tank reactors, were worked out while a series of papers from van Heerden [1] and Bilous and Amundson [2] through Uppal, Ray and Poore [3] and Schmitz, Graziani and Hudson [4] were studied. This experience provided a framework for interpretation of the strange events observed in Room 3. In fact, THL may have been the only student in that class who regarded autonomous oscillations as other than an academic hoax, for although experimental demonstrations had been alluded to in lectures, (perhaps) only he had actually observed them.

To further satisfy his curiosity, as well as the term paper requirement for his Process Dynamics course, THL conducted primitive experiments on the sink in Room 3. He measured level as a function of time with a meter stick and stop watch at various faucet flow rates which were measured with a graduated cylinder. He observed steady levels at low flow rates, oscillatory levels at intermediate flow rates and a return to steady levels at high flow rates. The oscillatory states were not truly periodic as the amplitudes and periods appeared to be randomly distributed, but over a fairly narrow range. THL was inclined to describe the oscillations as "chaotic" in light of the paper by Schmitz, Graziani and Hudson [4]. The source of the strange oscillations was not obvious, but the U-shaped trap in the drain line at the bottom of the sink was highly suspect.

To gain better insight into the oscillatory phenomena, a transparent model of a sink and drain was constructed, and a more exhaustive and







Thomas H. Leise earned his B.S. in Chemical Engineering from The Pennsylvania State University in 1979. He is currently employed as a production supervisor by Pfizer, Inc., Groton, Connecticut. **(L)**

Daniel J. Jenkins earned his B.S. in Chemical Engineering from The Pennsylvania State University in 1980. His presentation, "The Oscillating Sink," won the Judges Award for originality in research at the 1980 Mid-Atlantic AIChE Spring Conclave at Drexel University. He is presently working toward his M.S. in Chemical Engineering at Carnegie-Mellon University. His graduate research deals with synthetic fuels wastewater treatability and reuse. **(C)**

John M. Tarbell earned his Ph.D. in Chemical Engineering from the University of Delaware in 1974. He is currently an Associate Professor of Chemical Engineering at The Pennsylvania State University. His research interests are in process dynamics and stability, cardiovascular fluid dynamics, and chemical reactor modeling. **(R)**

Our main purpose in communicating this experience is to suggest a simple system, adaptable to a classroom or laboratory environment, which demonstrates some basic dynamic phenomena (instability, bifurcation, and oscillation).

accurate set of data was obtained by another of us (DJJ). We were amply rewarded for this effort as additional curious phenomena attendant to the oscillations were soon uncovered.

The apparatus, procedures and many of the results of these experiments are described in the following sections. Our main purpose in communicating this experience is to suggest a simple system, adaptable to a classroom or laboratory environment, which demonstrates some basic dynamic phenomena (instability, bifurcation, and oscillation).

APPARATUS AND PROCEDURES

A schematic of the experimental apparatus is shown in Fig. 1. A small, translucent, plastic holding tank was fitted with a drain which consisted of an elbow and two short pieces of metal tubing (~ .375″ i.d.) on the inside of the tank,

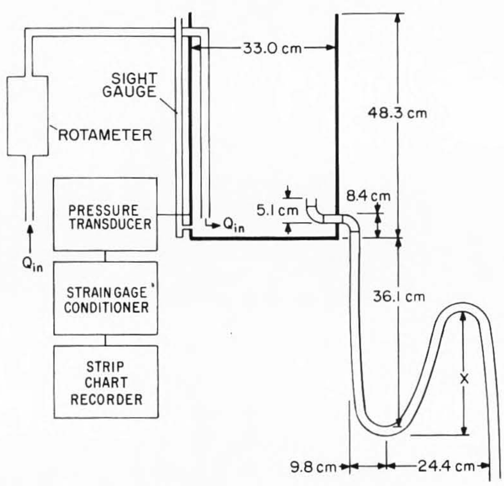


FIGURE 1. Experimental Apparatus.

with a length of flexible, transparent (Tygon) tubing (~ .375″ i.d.) on the outside. A bend of variable height (X) was maintained in the exit line with several clamps, and the line drained directly into a bench top sink. For most of the experiments, the drain inlet was oriented perpendicular to the tank bottom and open upward. An electronic pressure transducer was connected to the side of the tank below the level of the drain by means of a short piece of plastic tubing, and the instantaneous pressure was continuously re-

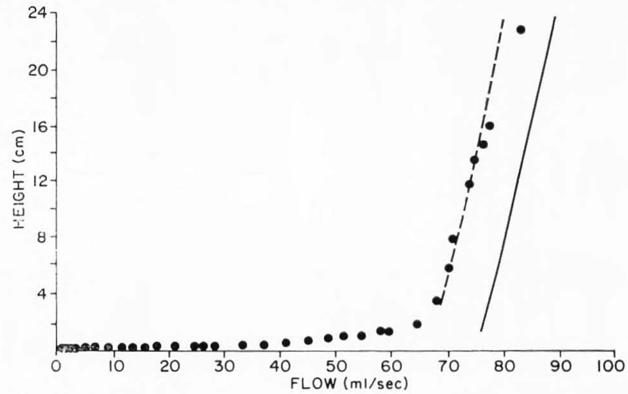


FIGURE 2. Height Versus Flow Rate (X = 0.0 cm.), Smooth Curve is from Mechanical Energy Balance with Friction Losses for Smooth Tubing and Bends. Dashed Curve Includes Drain Losses.

corded and assumed to be indicative of the instantaneous fluid level. Metered water flow was admitted to the tank through plastic tubing (~ .375″ i.d.) with the inlet maintained below the drain level in order to minimize splashing and associated noise.

Steady inlet flows were varied over a range from 0.5 m*l*/sec to 90 m*l*/sec resulting in Reynolds numbers in the outlet line up to 9,280 under steady level conditions. The bend height (X) was varied between 0.0 cm and 90.0 cm to provide conditions of: no bend, bend below the drain, and bend above the drain.

RESULTS AND DISCUSSION

A baseline case with no bend in the exit line (X = 0.0) was characterized by the data shown in Fig. 2. The ordinate is the height of the tank level above the drain and the abscissa is the steady inlet flow rate. The tank level was steady for all flow rates, but a rather marked steady state transition (bifurcation) occurred at ~ 65 m*l*/sec and a more subtle one at ~ 3 m*l*/sec. At flow rates between ~ 3 m*l*/sec and ~ 65 m*l*/sec, the exit line was in a two-phase (air/water) flow condition, while the flow became single-phase above 65 m*l*/sec. In the two-phase flow regime, there was a swirling vortex above the drain which sucked air into the exit line. As the flow rate was

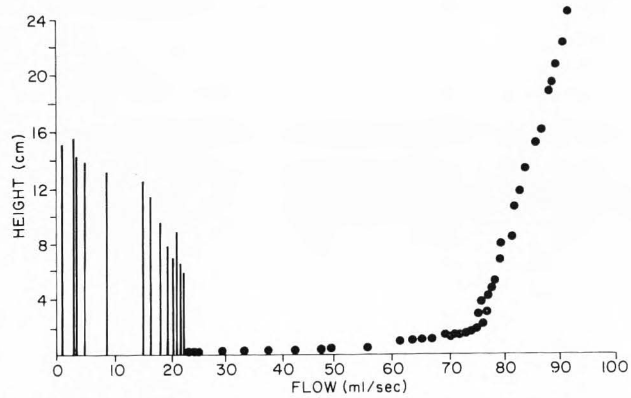


FIGURE 3. Height Versus Flow Rate (X = 41.4 cm.).

increased in this regime, the vortex contracted leading to diminished entrainment of air. As the flow rate was reduced below ~ 3 ml/sec, two-phase flow subsided and a slug of fluid remained stationary in the bottom of the U in the exit line with fluid trickling into and out of the slug.

The smooth curve in the high flow rate regime is based on the Mechanical Energy Balance incorporating friction factors for the smooth tubing and bends. When a loss coefficient of 2.0 is assigned to the drain, the dashed curve, which fits the single-phase flow data quite well, is obtained. Clearly, it is only in the high flow rate regime that the simple tank draining model of elementary process control [5] applies.

Fig. 3 shows the results of experiments with a 41.4 cm bend in the exit line. The vertical lines in the 4-25 ml/sec range represent oscillatory states. The oscillations were not truly periodic (perhaps chaotic?—see Fig. 4), and the heights of the vertical lines represent only average amplitudes. There are four bifurcations(changes in qualitative behavior) apparent in Fig. 3:

(1) Trickling steady states (with a stationary slug at the bottom of the U) transform to large amplitude oscillatory states at ~ 3 ml/sec;
(2) Large amplitude oscillatory states transform to small amplitude oscillatory states at ~ 12 ml/sec;
(3) Small oscillatory states become two-phase flow steady states at ~ 25 ml/sec; and
(4) Two-phase flow steady states become single phase flow steady states at ~ 65 ml/sec.

The observed physical mechanism of large amplitude oscillations is summarized in Fig. 5. Consider that an empty tank (and exit line) is being filled up, and the tank level has just reached the mouth of the drain (A). Fluid spills over the drain and fills up the U in the exit line as the level gradually rises (B). Eventually, fluid completely covers the drain trapping a column of air in the U (C). As the tank level rises, the air column is forced further down the tube until it passes around the bottom of the U. At this point the buoyant force of the rising air is sufficient to push fluid over the top of the bend (D). Once fluid passes over the top of the bend, a siphon is created and the tank quickly empties until the level has descended to the drain (E). Now air is sucked into the drain and a brief period of slug flow follows (F) until condition (C) is reestablished. At this point the cycle (C-F) repeats itself. The small amplitude oscillation mechanism is quite similar. The major difference is that the trapped air slug is smaller and the emptying is triggered by fluid passing over the top of the bend rather than air passing under the bottom of the U as in (D).

The transition from oscillatory to steady flow at 25 ml/sec can be understood if we realize that the siphon flow which drains the tank has a fixed rate determined by the configuration of the exit line. If the inflow rate exceeds the siphon flow rate, emptying is prohibited. The transition at 3 ml/sec

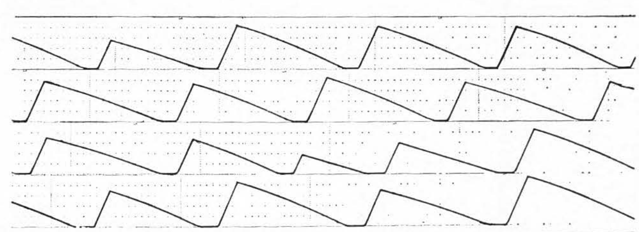


FIGURE 4. Height vs. Time Recording of Typical Oscillations (X = 21.6 cm., Flow Rate = 16.5 ml./sec.).

is not so easily understood. In fact, with the bend height set at X = 21.6 cm, oscillatory flows were observed down to our lowest inflow rate (~ 0.5 ml/sec) without a steady state transition (see Fig. 6). The results of Figs. 3 and 6 suggested the possibility of bi-stability (two stable flow regimes) in the low flow rate range, but limited hysteresis experiments did not reveal a range of coexisting steady and oscillatory states.

The effect of bend height on flow regimes was further investigated at X = 5.8, 30.1, 51.1, and 90.0 cm. Oscillations were observed for all bends, with their amplitudes strongly proportional to bend height. Steady states always existed at high flow rates, but with sufficiently high bend height, the two-phase flow regime disappeared. There was no obvious pattern in the appearance of low flow rate steady states. They appeared for X =

0.0, 5.8, 41.4 and 51.1 cm, but not for X = 21.6, 30.1 and 90.0 cm.

In a final desperate attempt to eliminate oscillations with a finite bend, we inverted the drain to an open downward configuration thinking that this would eliminate the sucking of air which was considered vital to the oscillation mechanism. To our surprise, the siphon effect was strong enough to suck air around the inverted drain, and we observed oscillations following the mechanism of Fig. 5. We conclude that the only way to completely eliminate the oscillatory regime is to completely eliminate the bend.

CONCLUDING REMARKS

If you are interested in practical engineering applications for our sink, you might consider it as a primitive level controller when operated in the two-phase flow regime, where level is nearly independent of inflow rate, or, as a periodic feed pump to a batch process when operated in the oscillatory flow regime.

On the other hand, if you are looking for theoretical significance, you should realize that it is an unusual hydrodynamical system in which intermediate time-dependent states are surrounded by steady states at both lower and higher values of a parameter. For example, in pipe flow there is a transition from steady (laminar) flow to time-dependent (turbulent) flow as the Reynolds number is increased, but a return to steady flow at higher Reynolds numbers is not observed. The same may be said of the classical Taylor (circular couette) and Rayleigh-Bénard (heated layer) flows [6]. As the Taylor or Rayleigh number is increased, a bifurcation from steady to time dependent motion occurs, but further parameter increase does not result in steady motion. Intermediate time dependent states are readily observed in chemical reaction systems. For example, a constant volume continuous stirred tank reactor (CSTR) always produces stable steady states at sufficiently high and low values of the flow rate [7, 8], but time-dependent states may occur at intermediate flow rates [4].

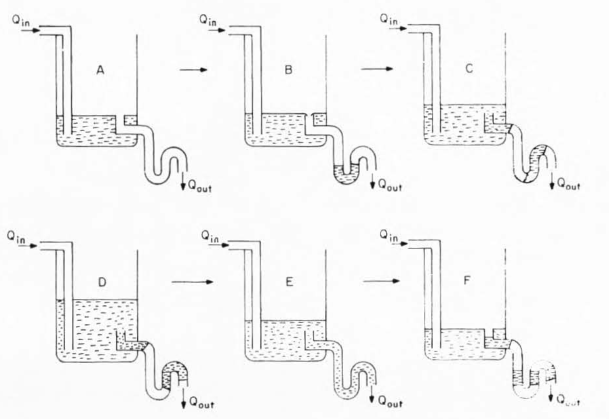


FIGURE 5. Schematic of the Oscillation Mechanism.

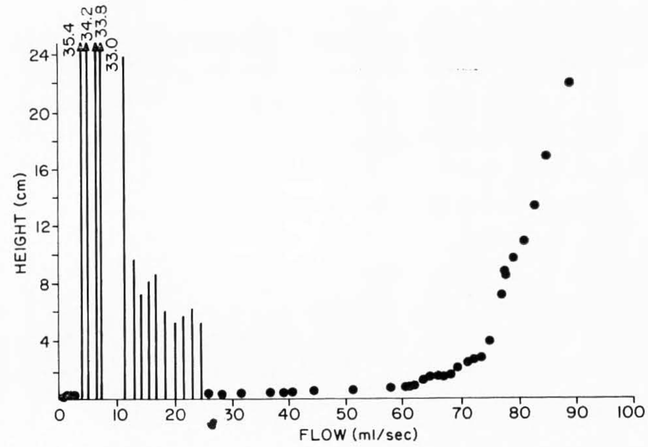


FIGURE 6. Height Versus Flow Rate (X = 21.6 cm.).

Finally, if your interests are pedagogical, "the oscillating sink" provides a simple demonstration of autonomous oscillations and a variety of bifurcation phenomena. As a parting note, the demonstration value of the oscillating sink can be improved by the use of a smaller diameter tank than we have shown in Fig. 1. This will result in shorter oscillation periods (we observed periods of several minutes) and a more dynamic demonstration. The tank diameter should not affect the oscillation mechanism. □

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The object of this column is to enhance our readers' collection of interesting and novel problems in Chemical Engineering. Problems of the type that can be used to motivate the student by presenting a particular principle in class or in a new light or that can be assigned as a novel home problem are requested as well as those that are more traditional in nature that elucidate difficult concepts. Please submit them to Professor H. Scot Fogler, ChE Department, University of Michigan, Ann Arbor, MI 48109.

MELTING ICE CUBES PROBLEM

JUDE T. SOMMERFELD AND
PETER A. MINDERMAN
Georgia Institute of Technology
Atlanta, GA 30332

A certain chemical reaction is being carried out in the aqueous phase in a 2000-gal. reactor. The reactor is half-full and its contents are maintained at the reaction temperature of 100°F.

At a certain point in the reaction, it is desired to quench the reaction as rapidly as possible. For this purpose, the rapid dumping of 2000 lbs. of 1-inch ice cubes (at 32°F) into the reactor contents has been proposed. Calculate 1) how long it will take for all of the ice to melt and 2) what the final solution temperature will be at this time.

Prior laboratory experiments under similar conditions of agitation have shown that the overall coefficient for heat transfer at the ice surface is 200 BTU/hr.–ft^2–°F. The latent heat of fusion of ice is 144 BTU/lb., while its density is 57.5 lbs./ft^3. The physical properties of the aqueous solution may be assumed to be the same as those for water. A sketch of this system is presented in Fig. 1.

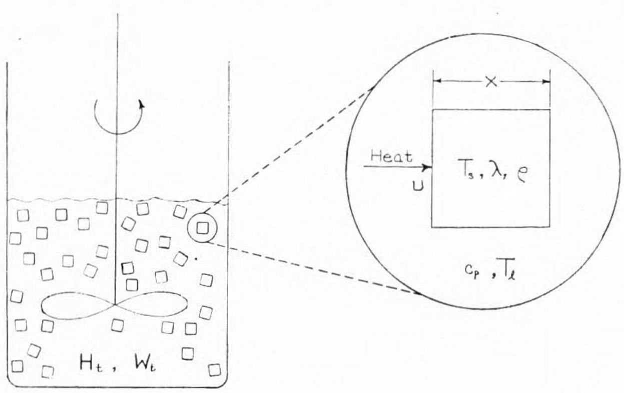
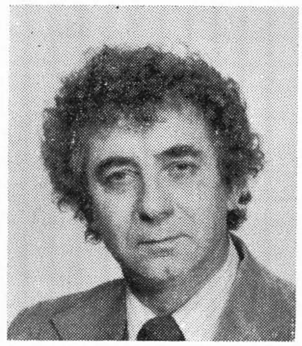
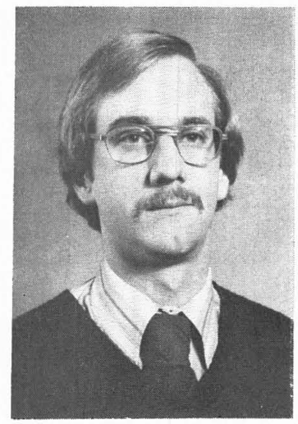


FIGURE 1. Sketch of the physical system in the melting ice cubes problem.





Jude T. Sommerfeld has been a professor of ChE at Georgia Tech since 1970. He teaches courses on process control, distillation, reactor design and process design, and his research interests include energy conservation. He has also served as a consultant to numerous industrial organizations. Prior to 1970 he had eight years of engineering and management experience with the Monsanto Company and BASF-Wyandotte Corp. Dr. Sommerfeld received his B.Ch.E. degree from the University of Detroit, and his M.S.E. and Ph.D. degrees in chemical engineering from the University of Michigan. **(L)**

Peter A. Minderman Jr. received his B.S. from Georgia Tech in 1979 and MS from the same institute in 1981. His prior industrial experience includes work with DuPont and Tennessee Eastman Co., a division of Eastman Kodak. He has recently returned to Tennessee Eastman and currently works in the Process Systems Engineering group. **(R)**

SOLUTION

The basis of the solution consists of an enthalpy balance around the solid (ice) phase. The liquid phase at the melting temperature of the solid phase is chosen as the enthalpy reference state. With this choice, the specific enthalpy (BTU/lb) of the liquid phase is equal to $c_p(T-T_s)$. Similarly, the specific enthalpy of the solid phase becomes the negative of the latent heat of fusion ($-\lambda$). Essential to the foregoing statement is the assumption that the temperature of the solid phase is always at its melting point. The rate of heat input (BTU/hr) to the solid phase is then

$$UA\ (T - T_s)$$

while the rate of accumulation is

$$-\lambda \frac{dW_s}{dt}$$

There is no heat output from the solid phase as well as no generation or consumption terms. Hence, the differential enthalpy balance equation becomes

$$UA\ (T - T_s) = -\lambda \frac{dW_s}{dt} \tag{1}$$

It is assumed that the ice cubes are truly cubical in shape and further that they remain cubical as they melt. That is, there exists no preferential melting at any one face of the cube. Assuming that all of the cubes behave identically, the total number of cubes then also remains constant as long as ice is present. It then follows from these assumptions that

$$W_s = \rho N x^3$$

and

$$A = 6Nx^2$$

The result of substituting these equalities into Eq. (1) is

$$\frac{dx}{dt} = \frac{-2U}{\rho\lambda}(T - T_s) \tag{2}$$

It remains then to relate the temperature of the solution (T) to the size of the melting ice cubes (x). This is achieved by performing material and enthalpy balances around the complete system. The material balance is

$$W_s + W_l = W^o_s + W^o_l = W_t\ (= \text{const})$$

or

$$W_l = W_t - W_s \tag{3}$$

And assuming adiabatic operation, the enthalpy balance is

$$H_s + H_l = H^o_s + H^o_l = H_t\ (= \text{const})$$

or

$$H_l = H_t - H_s$$

Now

$$H^o_l = W^o_l c_p (T_o - T_s)$$
$$H^o_s = -\lambda W^o_s$$
$$H_l = W_l c_p (T - T_s)$$
$$H_s = -\lambda W_s$$

Hence

$$H_t = W^o_l c_p (T_o - T_s) - \lambda W^o_s$$

and

$$W_l c_p (T - T_s) = H_t + \lambda W_s \tag{4}$$

Substitution of Eq. (3) for W_l into Eq. (4) and rearrangement of the result leads to

$$T - T_s = \frac{H_t + \lambda W_s}{c_p (W_t - W_s)} \tag{5}$$

Finally, substitution of the above result into Eq. (2) yields

$$\frac{dx}{dt} = \frac{-2U}{\rho\lambda}\left[\frac{H_t + \lambda W_s}{c_p (W_t - W_s)}\right]$$

or

$$\frac{dx}{dt} = \frac{-2U}{\rho c_p}\left[\frac{(H_t/\lambda\rho N) + x^3}{(W_t/\rho N) - x^3}\right] \tag{6}$$

Before proceeding to the integration of Eq. (6), it is convenient to make the following definitions

$$\alpha = \frac{2U}{\rho c_p}$$

$$\beta^3 = \frac{H_t}{\lambda\rho N}$$

$$\gamma^3 = \frac{W_t}{\rho N}$$

whence

$$\frac{dx}{dt} = -\alpha\left[\frac{\beta^3 + x^3}{\gamma^3 - x^3}\right] \tag{7}$$

If one now defines a new dependent variable as

$$y = \frac{x}{\beta}$$

the result upon insertion into Eq. (7) is

$$\frac{dy}{dt} = -\frac{\alpha}{\beta}\left[\frac{1 + y^3}{\gamma^3/\beta^3 - y^3}\right]$$

And finally with the following additional definitions

$$c = \frac{\alpha}{\beta}$$

$$a = \frac{\gamma^3}{\beta^3}$$

one has

$$\frac{dy}{dt} = -c\left[\frac{1 + y^3}{a - y^3}\right] \tag{8}$$

The integration of Eq. (8) is given in any comprehensive table of integrals. The result is

$$ct = \left[y - \frac{(a+1)}{3}\left\{\frac{1}{2}\ln\frac{(1+y)^2}{1 - y + y^2} + \sqrt{3}\ \mathrm{TAN}^{-1}\left(\frac{2y - 1}{\sqrt{3}}\right)\right\}\right]_{y_o}^{y} \tag{9}$$

where

$$y_o = \frac{x_o}{\beta}$$

For the particular case wherein the upper limit of integration is zero (that is, complete melting of the solid phase), Eq. (9) assumes the following form

$$ct\ (y=0) = \frac{a+1}{3}\left[\frac{1}{2}\ \ln \frac{(1+y_o)^2}{1-y_o+y_o^2} + \sqrt{3}\ \mathrm{TAN}^{-1}\left(\frac{\sqrt{3}\ y_o}{2-y_o}\right)\right] - y_o \qquad (10)$$

for which the following trigonometric identity was invoked

$$\mathrm{TAN}\ (u-v) = \frac{\mathrm{TAN}\ (u) - \mathrm{TAN}\ (v)}{1 + [\mathrm{TAN}\ (u)]\cdot[\mathrm{TAN}\ (v)]}$$

The original problem concerned the quenching of 1000 gallons of an aqueous solution originally at 100°F. The physical properties of the solution were assumed to be the same as those for water. It was proposed to dump 1 ton of 1-inch ice cubes into the solution at quench time. The various problem parameters then assume the following values

$$W_t = (1000)\ (8.33) + 2000 = 10{,}330 \text{ lbs}$$

$$H_t = (1000)\ (8.33)\ (1.0)\ (100-32) - (144)\ (2000) = 278{,}000 \text{ BTU}$$

$$N = \frac{(2000)\ (12)^3}{(57.5)\ (1.0)^3} = 60{,}100$$

$$\alpha = \frac{(2)\ (200)}{(57.5)\ (1.0)} = 6.96 \text{ ft/hr}$$

$$\beta^3 = \frac{278{,}000}{(144)\ (57.5)\ (60{,}100)} = 0.558\cdot10^{-3} \text{ ft}^3$$

$$\beta = 0.0823 \text{ ft}$$

$$\gamma^3 = \frac{10{,}330}{(57.5)\ (60{,}100)} = 2.995\cdot10^{-3} \text{ ft}^3$$

$$\gamma = 0.1441 \text{ ft}$$

$$a = \frac{2.995\cdot10^{-3}}{0.558\cdot10^{-3}} = 5.37$$

$$c = \frac{6.96}{0.0823} = 84.6 \text{ hr}^{-1}$$

$$y_o = \frac{1}{(12)\ (0.0823)} = 1.012$$

Substitution of the last three quantities into Eq. (10) then results in the following time required for complete melting of the ice (solid phase)

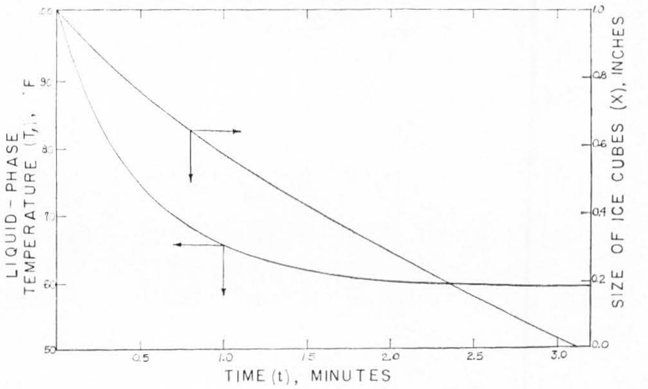


FIGURE 2. Time histories for the size of the ice cubes and the liquid-phase temperature.

$$t\ (x=0) = 0.0514 \text{ hr} = 3.08 \text{ min.}$$

The temperature of the quenched aqueous phase at this time is given via algebraic solution of Eq. (5) with $W_s = 0$; the result is 58.9°F.

Complete time histories for the size of the ice cubes and the liquid-phase temperature for this particular system are presented in Fig. 2. □

NOMENCLATURE

- a — γ^3/β^3
- A — total surface area of unmelted solid phase, ft^2
- c — α/β
- c_p — heat capacity of liquid phase, BTU/lb–°F
- H — enthalpy, BTU
- N — total number of solid-phase cubes
- t — time, hr
- T — temperature, °F
- U — overall coefficient for heat transfer from the liquid phase to the solid phase, BTU/hr–ft^2–°F
- W — mass of material, lbs
- x — size of a solid-phase cube, ft
- y — x/β
- α — $2U/\rho c_p$
- β — $\sqrt[3]{H_t/\lambda\rho N}$
- γ — $\sqrt[3]{W_t/\rho N}$
- λ — latent heat of fusion of solid phase, BTU/lb
- ρ — density of solid phase, lbs/ft^3

SUBSCRIPTS

- l — liquid phase
- o — initial condition (t = 0)
- s — solid phase
- t — total (sum of liquid + solid phases)

SUPERSCRIPT

- o — initial condition (t = 0)

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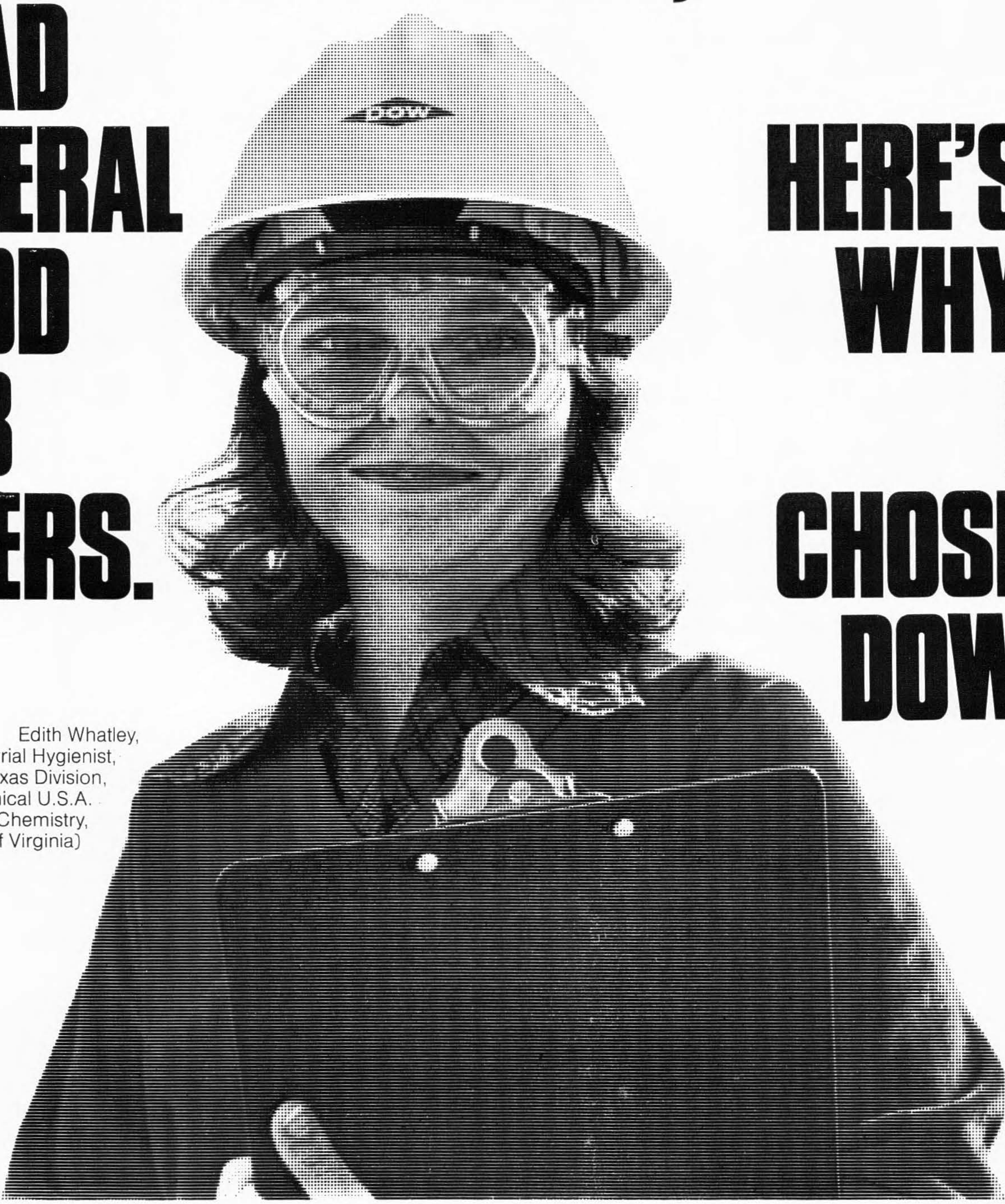

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Edith Whatley,
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(M.S. Chemistry,
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DIGITAL COMPUTER APPLICATION IN PROCESS CONTROL

M. F. ABD-EL-BARY AND SRIRAM CHARI
New Jersey Institute of Technology
Newark, NJ 07102

WITH THE RAPID DEVELOPMENT and extensive use of Direct Digital Control (DDC) in industry, smaller versions of digital computers equipped with laboratory modules are being utilized increasingly in undergraduate Process Control laboratories to train chemical engineers in the theory and practice of digital control. It was pointed out by Waller [1], however, that the thrust of process control teaching is still directed toward very basic facts only, and that old textbooks were being used to a large extent. Newer textbooks and laboratory experiments should, therefore, emphasize computers and digital systems.

One of the chief reasons for the popularity of digital computers is the "amplifier-limitation"

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Sriram Chari is an MBA student at the Harvard Business School. He has a B.S.ChE from Indian Institute of Technology, Delhi, and an M.S.ChE from New Jersey Institute of Technology. He was a Shift Engineer at Swadeshi Polytex Limited in Ghaziabad, India, before working on this project as a Teaching Assistant at NJIT. **(R)**

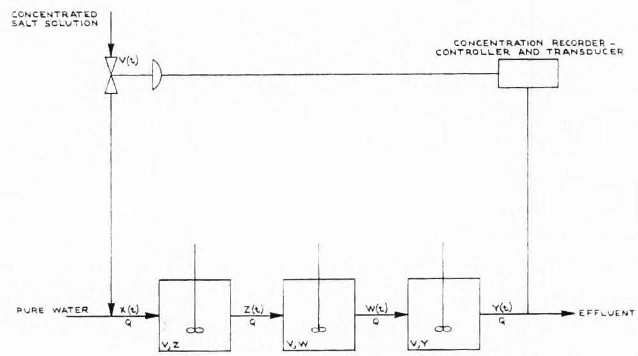

FIGURE 1. Schematic of three CSTR's

disadvantage of analog computers. Complex control systems, such as P-I-D Control, for example, require a large number of amplifiers, sometimes more than that which is available in smaller analog computers. A digital computer can resolve this difficulty by simulating the control logic through its software. In the Process Control laboratory at New Jersey Institute of Technology, a digital computer has been hooked up with an analog computer to give students an overview of the advantages and disadvantages of both computers in a single experiment.

An EAI-20 analog computer was used to simulate a system of three CSTR's in series. The first CSTR is fed with a brine solution stream and a fresh water stream. The salt concentration of the third CSTR outlet stream is controlled by regulating the flow of brine to the first CSTR, as shown in Fig. 1. The original set up involved only proportional control. The stability of the system is studied by observing its response to a unit step change in the set point. Writing a material balance and performing magnitude scaling leads to the final analog equation:

$$\frac{-d}{dt}[20Y''] = 6[20Y''] + 2.4[100Y'] + 0.32[500Y] + 0.16K_c[2(500Y)-1]$$

where Y is the Laplace transform of the controlled variable, and K_c is the Proportional Controller gain (psi/mv). Fig. 2 shows the analog patch diagram corresponding to the above equation. The proportional controller gain (K_c) was adjusted by means of potentiometer number 15, set at .016 K_c. Marginal stability resulted at a gain of 8 psi/mv, a value that was close to that obtained by analytical stability calculations such as the Routh test.

Recently, the department acquired a Digital MINC-11 minicomputer equipped with four laboratory modules: a preamplifier, an analog to digital (a/d) converter, a clock, and a digital to analog (d/a) converter. The two computers were connected so that the use of potentiometer number 15 of the analog computer was done away with, and the original input to the potentiometer became the input to the digital computer, which acted as the controller. For proportional control, the input analog signal was sent in through one of the a/d channels, converted to a digital signal by the a/d converter, and then multiplied by a constant (K_c). The resultant digital signal was converted to its analog counterpart before the

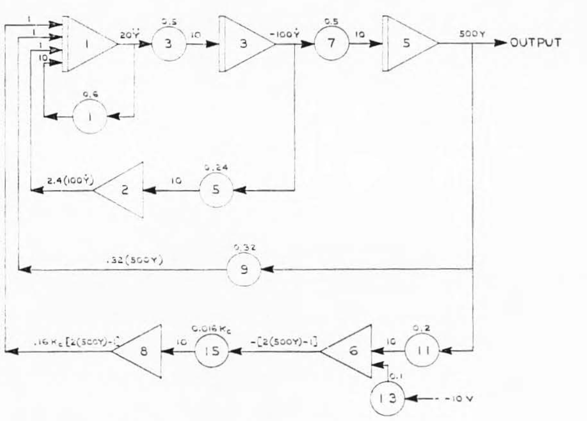

FIGURE 2. Analog Patch Diagram

latter was sent out to the analog computer as a substitute for the output of potentiometer number 15.

Addition of other modes of control such as Manual, Proportional-Integral, P-I-D, and P-D were made easily. For P-I, for example, the input signal was integrated by Simpson's Rule and the necessary additions and multiplications performed. For P-D control, on the other hand, the input signal was differentiated. In addition to achieving different modes of control, the digital computer was also used to monitor the analog computer

One of the chief reasons for the popularity of digital computers is the "amplifier-limitation" disadvantage of analog computers. Complex control systems, such as P.I.D Control . . . require a large number of amplifiers, sometimes more than that which is available in smaller analog computers.

output. Another channel of the analog/digital converter served this purpose.

SAMPLING FREQUENCY

The frequency of sampling of the input analog signal was made as high as possible by using a loop in the BASIC program similar to a DO loop in FORTRAN. The clock module in the digital computer could have been used to obtain even higher sampling rates, but its disadvantage is that processing of the already collected data cannot simultaneously take place. Thus, the clock will allow the collection of 50 sample points at a very high rate, but will then *wait* for these data points to be processed and for the output signal to be sent out before collecting another 50 sample points. Between two processings enough time elapses to render a fast process unstable.

In the sampling method adopted in this experiment, one sample point (V_2) was collected at the start of each loop, and used along with the last sample point (V_1) to perform differentiation and other operations. On the basis of these operations an output signal was formulated and sent out, and the next loop began with the collection of a new data point. This new point was stored as V_2, and the old value of V_2 transferred to V_1. This way, the two latest sample points are processed in each loop. A sampling rate of approximately one sample every 0.12 seconds could be achieved by this method. In addition, a PAUSE statement was incorporated in the program to introduce a time delay, and thus vary the sampling rate. Therefore, the effect of the sampling frequency on the system response could also be studied.

RUNNING

With the analog and the digital computers hooked up together, the digital computer was started first with the values of K_c, Integral Time (τ_I), and Derivative Time (τ_D) specified. At a preset time the analog computer was put on

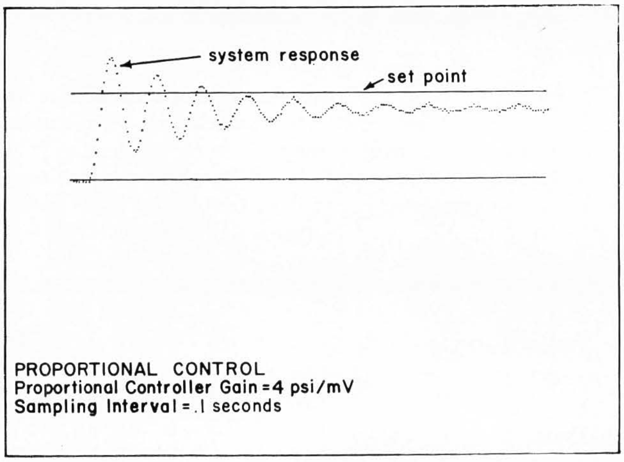

FIGURE 3

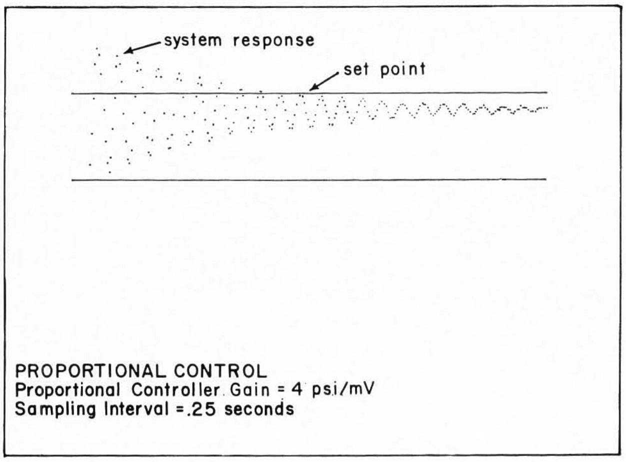

FIGURE 4

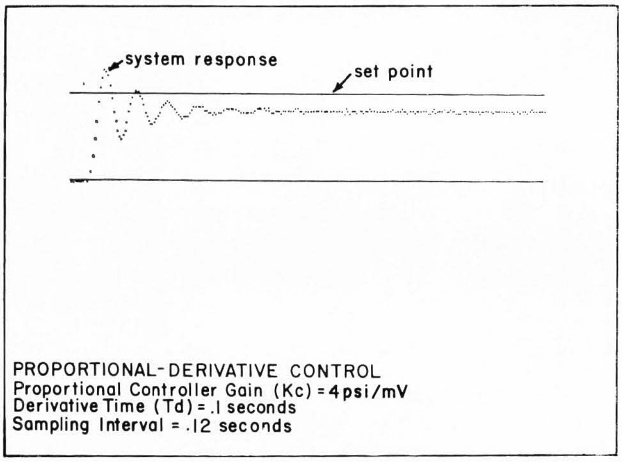

FIGURE 5

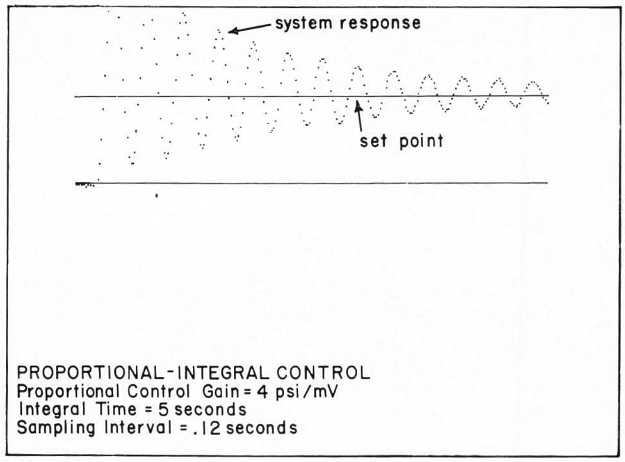

FIGURE 6

"Operate" mode. The response of the system could then be monitored on the video terminal. A Textronix Hard Copy Unit was used for immediate reproduction of the video projection.

DISCUSSION

The most striking (and only apparent) disadvantage of digital control is that, at best, the sampling frequency only approximates continuous analog sampling. This disadvantage is very pronounced in controlling fast processes. For example, if the residence time in each CSTR is 0.5 minutes, the proportional controller gain (K_c) for marginal stability is 5.25 psi/mv for a sampling period of 0.1 second, as compared to a value of 8.0 psi/mv obtained with continuous analog sampling. Increasing the sampling frequency to 0.25 seconds reduced the marginal stability value of K_c to 4.35 psi/mv. The use of discrete sampling through the addition of digital computer, therefore, decreases the proportional controller gain for marginal stability. Luyben [2] shows how this addition introduces, in effect, a process lag and hence increases instability.

This experiment allows the student to get a better understanding of control theory since the control is done through obvious softwave instead of the (black box) analog controller. Students can study the effect of varying sampling interval (through the use of PAUSE statement) on the performance of the system. By plotting the set point and the controlled variable on the CRT, the concept of offset, and oscillatory response can be shown much more clearly. In Figs. 3, 4, 5, 6, and

7 the lower horizontal line represents the initial value of the variable, while the upper horizontal line represents the set point. Fig. 3 shows an offset, representing the behavior of the system with proportional control, and Fig. 4 shows more oscillatory response as the sampling frequency was increased. Fig. 5 represents the response with P-D control, showing better response over proportional control. Fig. 6 shows no offset with P-I control while Fig. 7 represents the response with

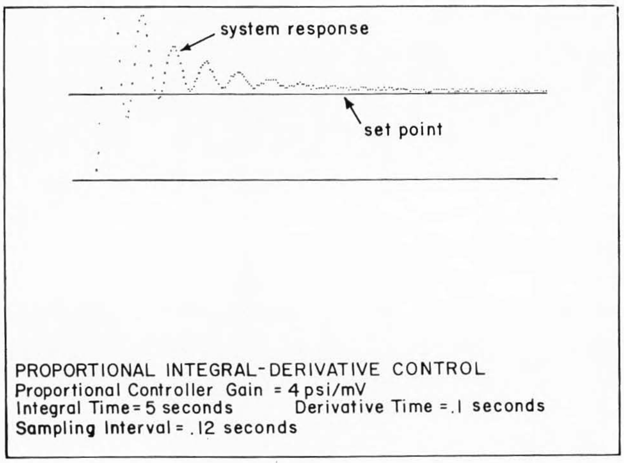

FIGURE 7

P-I-D control. The best response is clearly obtained with P-I-D control.

Another point to be taken into consideration is that a complex mode of control requires more amplifiers than can be provided by a small analog computer. This difficulty can be overcome by hooking up a digital computer together with it. In fact, there is no end to the modes of control that can be simulated by a digital computer used in conjunction with even as small an analog computer as an EAI-20.

ACKNOWLEDGMENT

Partial support for equipment purchased was provided by Exxon. The authors acknowledge helpful suggestions provided by Prof. E. C. Roche. □

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ChE book reviews

THE MATHEMATICAL UNDERSTANDING OF CHEMICAL ENGINEERING SYSTEMS— SELECTED PAPERS OF NEAL R. AMUNDSON
Edited by R. Aris and A. Varma
Pergamon Press, 1980. 830 pages

Reviewed by John H. Seinfeld
California Institute of Technology

Neal Amundson has exerted a profound influence on the course of modern chemical engineering. As virtually a lone pioneer in the late 1940's and early 1950's, he opened the frontier of the mathematical understanding of chemical engineering systems. Although legions have rushed in behind him, a vast number of the Chief's own papers remain the seminal milestones along the path that has led slowly and steadily to a rigorous mathematical description of chemical engineering processes. This volume, prepared with love and care by Rutherford Aris and Arvind Varma, is a Baedeker for the traveller retracing that path.

Of over 2000 pages of Amundson's published papers, Aris and Varma have selected 800 for reprinting. For those papers not reproduced in their entirety, leading pages, with the usual abstract, and sometimes pages containing conclusions or summarizing statements, are included. The scope of the papers is impressively broad, including major contributions in ion exchange and chromatography, distillation, chemical reactor stability and control, polymerization reaction engineering, the modeling of fixed and fluidized bed reactors, steady state uniqueness and multiplicity of catalyst particles and chemical reactors, and the combustion of single carbon particles.

The modeling of physical systems is, as Aris has noted, an art and a craft, and Neal Amundson stands as the senior artist and craftsman in the modeling of chemical engineering systems. In his analysis of complex systems Amundson has always sought the mathematical description that captures the fundamental essence of the system's behavior, the art of selecting the proper balance between simplicity and reality. Once a model has been chosen, the elucidation of its properties can be attacked with all the heavy machinery of mathematics, the craft of the modeler. This

Continued on page 125.

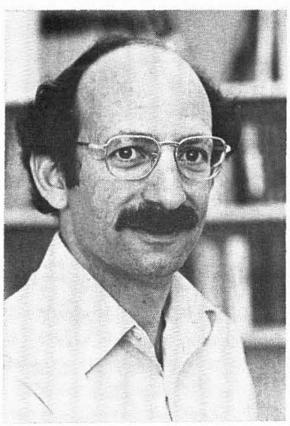
THE DEVELOPMENT OF COMMUNICATIONS SKILLS THROUGH A LABORATORY COURSE*

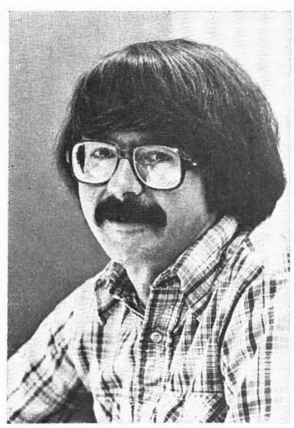
CURTIS W. FRANK
GEORGE M. HOMSY
CHANNING R. ROBERTSON
Stanford University
Stanford, CA 94305

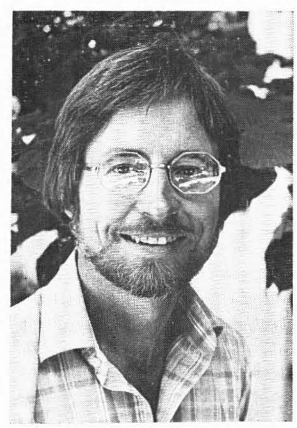
FEW WOULD DISPUTE THE obligation of departments of chemical engineering to provide students with a sound technical education in the fundamentals of thermodynamics, heat, mass and momentum transfer, separations processes and chemical reaction engineering. That schools in this country have been successful in doing so is indicated by the high level of industrial competition for new graduates. However, despite the facility with which a young working engineer performs design calculations or process analyses, such efforts will prove fruitful only if they are communicated effectively to others. In fact, in a recent survey of prominent engineers, 95% of the respondents indicated that writing ability played either a very important or a critically important role in their work. [1] Unfortunately, training in communications skills for engineers in most colleges and universities is relegated to the two or three courses in Freshman English required of all students to graduate. Even if courses in technical communication were available, the typical chemical engineering curriculum is highly structured and such an option, regardless of its merits, faces stiff competition from other free electives. A natural alternative to requiring an additional writing course is the incorporation of an emphasis on communication skills into the laboratory course. Such an approach has been followed in the Department of Chemical Engineering at Stanford since 1978.

The present configuration of our undergraduate laboratory has evolved as a result of concerted efforts to teach good communication. It was neces-

*This paper originally appeared, in somewhat different form, as an article in the 1982 Compendium on Engineering Laboratory Instruction.







George M. Homsy is a Professor of Chemical Engineering at Stanford University. He did his undergraduate work at the University of California at Berkeley, receiving his B.S. in 1965. His graduate training was at the University of Illinois from which he received his M.S. in 1967 and PhD in 1969. His research program consists of theoretical and experimental studies on flow instabilities at interfaces, convection in fluids which is due to surface tension or density gradients and in fluid particle systems such as fluidized beds and porous media. **(L)**

Curtis W. Frank is an Associate Professor of Chemical Engineering at Stanford University. He did his undergraduate work at the University of Minnesota, receiving his B. Chem. Eng. in 1967. His graduate studies were performed at the University of Illinois, from which he received the M.S. in 1969 and PhD in 1972. His research program in polymer physics includes projects in the thermodynamics of amorphous polymer blends, intramolecular rotational motion and polymer-solvent interactions in dilute solution and the synthesis and morphology of poly (vinylidene fluoride). **(M)**

Channing R. Robertson is Professor and Chairman of the Department of Chemical Engineering at Stanford University. He completed his B.S. at the University of California at Berkeley in 1965, and then went to Stanford from which he obtained his M.S. in 1967 and PhD in 1970. His research interests in bioengineering include projects in transport phenomena in mammalian kidneys, artificial kidney components, immobilization of whole cells, biocompatible materials and membrane transport processes. **(R)**

sary, however, to first ensure that the experiments were of uniformly high quality. In 1978 the department received an Instructional Scientific Equipment grant from the National Science Foundation. This grant, with additional funds from the Stanford School of Engineering, the Department of Chemical Engineering and a Special Program Grant from the Dreyfus Foundationtion, allowed new instrumentation to be purchased so that new experiments in chemical reaction engineering and polymer materials science could be developed and existing ones upgraded. Second, in a major commitment of department resources, a new position was created for a technician whose primary responsibility would be the undergraduate laboratory, his duties to include routine maintenance, renovation of existing apparatus and design and fabrication of new instrumentation. Third, three existing laboratory courses were formally dropped from the curriculum, their best experiments added to those developed under NSF support in a new six unit two quarter sequence. These actions allowed strong emphasis on the development of oral and written communication skills.

A key element in the new laboratory course has been the assistance provided by the Communications Project of the School of Engineering at Stanford University. [2] This is an innovative program, initiated in September 1976, and designed to assist engineering students in improving their writing and speaking abilities. Among other things, the Communications Project involves person-to-person tutorials and the rewriting of graded reports, features which have been made integral parts of our laboratory course. The unique aspect of the Communications Project is that the communications tutors are not professional staff members; they are undergraduate engineering students who have been specially selected on the basis of their writing and speaking talents and then given instruction to hone their abilities further. The underlying philosophy is that the tutors act as role models with whom the students may closely identify.

COURSE ORGANIZATION

In order that the students have an appropriate technical background for the experiments, the course sequence is given in the winter and spring quarters of the senior year after all necessary lecture courses have been taken. A total of twelve experiments in five different areas have been developed to date. These include fluid mechanics (determination of flow profiles using Laser-Doppler velocimetry, drag force on spheres), heat transfer (transient and steady conduction, forced convection, radiative energy transport), mass transfer (steady diffusional mass transfer), chemical reaction engineering (isothermal batch reactor, tubular reactor, continuous flow stirred tank reactor), and polymer materials science (viscoelastic creep, dilatometric measurement of glass transition temperature, differential scanning calorimetry). Four faculty members are associated with the course, with two sharing responsibility for the experiments each quarter. In addition, there are two graduate teaching assistants each quarter, one working with each faculty member. Finally, there are one or more peer tutors from the Communications Project in both the written and oral skills areas.

. . . in a recent survey of prominent engineers, 95% of the respondents indicated that writing ability played either a very important or a critically important role in their work.

The experiments are carried out by groups composed of three students with each group performing eight experiments during the two quarter sequence. For each experiment one person acts as group leader and the other two as assistants. Although all group members should be conversant in the underlying theory, the group leader bears ultimate responsibility for the successful completion of the experiment. He must ensure that the instrumentation is operating properly, that the appropriate data are taken and that the calculations, shared among all group members, are done correctly. The team concept is an important element of the course. Efficient group operation in the planning, execution and analysis of each experiment requires effective intragroup communication and close cooperation. In its ideal form, this experience provides a model for the student in his later professional activities, e.g. as an engineer on a process design team. Finally, since organizational responsibilities and reporting requirements are rotated among group members throughout the two quarters, each student receives multiple exposure to several forms of expression, both written and oral.

COMMUNICATION SKILLS DEVELOPMENT

The philosophy behind the reporting procedures (to be described shortly) is that development of writing and speaking skills requires extensive practice, i.e. learning by doing. Moreover, the student must make an active effort to comprehend his errors and to correct the problems through rewriting his reports until the presentation is clearly organized. An essential part of the educational process is the tutorial session in which the student meets individually with a writing and/or speaking tutor from the Communications Project, as appropriate. The tutorial session can serve as a device to assist in preparation such as a preview of an oral presentation or after the fact as a means of evaluating clarity of presentation in a report which has already been graded for technical content. To assist the students in understanding the level of faculty expectations

Perhaps the most important skill learned is the ability to present results and conclusions clearly and concisely in a short written report or oral presentation.

for written and oral reports, a course syllabus is provided in which guidelines are given. In addition, during the first week of the course winter quarter, before the experiments begin, some lectures are devoted to fundamentals of communications skills. The students are also advised to obtain and read *The Elements of Style*, by William Strunk and E. B. White, 3rd. ed., MacMillan Publishing, New York, 1979 before the experiments begin. This small text is concise and quite readable; in fact, it serves as a good model of the objectives for the written reports.

Since this course has only been offered a limited number of times in its present form, it is still evolving. The following description applies to the course which was offered during the 1979-80 academic year in which four distinct forms of communication were utilized. Three of these were written and one oral. The most extensive written document is the major technical report which is required of the group leader for each of the first six experiments. This report presents the theoretical background, objectives, laboratory procedure, results, conclusions and recommendations in a style typical of a journal article. Although this document is a major undertaking, the student must exercise judgment in determining the depth of coverage warranted for a particular experiment. Since there are three persons to a group, each student does two of these major reports during the first six experiments. The major report is graded twice: once for technical accuracy and once for effectiveness of communication. The first person to read the report is one of the graduate teaching assistants who prepares a critique emphasizing technical accuracy. The report is then examined by the faculty member in charge of the experiment, again mainly for technical purposes. However, if the report organization is so confusing that it is not possible to determine whether the student comprehended the intent of the experiment, the report is returned to the student for rewriting. Upon resubmission, the faculty member and teaching assistant agree on a grade on the technical content which is up to 75% of the total possible points. The report is then returned to the student who must make an appointment with the writing tutor from the Communications Project. In this second evaluation phase the tutor will go through the report individually with the student and examine it solely for clarity of communication. After this tutorial session, the student is usually required to rewrite sections, or even the entire report. After resubmission, the tutor assigns a grade, up to 25% of the total possible points, on the basis of the degree to which the student has complied with the suggestions made during the tutorial session.

The second written form of communication is a brief technical summary required of each of the assistants. This is strictly limited to 300 words in length and should provide a clear and concise description of how the objectives were met and the major results. No supporting graphs or tables are permitted and the use of equations is discouraged. The grading of this report, both for technical accuracy and for effectiveness of communication, is done by the faculty member and teaching assistant. Again, the report usually has to be rewritten before a final grade is assigned. Each student will do four of these technical summaries over the first six experiments.

The third form of written report is used during the last two experiments of the second quarter. This is a short technical report or extended abstract which is prepared by each of the group assistants. The report is three to five pages long and includes a brief theoretical background, objectives, presentation of results by means of graphs and tables and discussion of the observations and conclusions. Each student does one or two of these reports.

The oral communication exercise is a ten minute talk which is required of one of the two assistants for each of the first six experiments and of the group leader for the last two. Thus, each student presents at least three and perhaps four talks over the two quarter sequence. Heaviest use of the Communications Project tutors is made in this phase of course activity, e.g. in 1979-80 there were three speaking tutors for a class of 29 students. The student presents his talk first to the speaking tutor individually and then to the entire class during one of the two weekly lecture periods. Immediately after the presentation, questions of a technical nature are posed by the general audience. Then two previously selected class members give oral critiques of the communications aspects of the talk. Finally, each faculty member, teaching assistant, speaking tutor and student evaluator fill out grading forms on the structure of the talk, use of visual aids, delivery and technical content. A summary of these written evaluations is given to each student.

Although the course is only two years old, it has become a focal point for the synthesis of other elements of the undergraduate program. It differs appreciably, however, from the orientation of the traditional engineering courses, which typically emphasizes mastery of the technical aspects of a subject. Although development of sound experimental technique is certainly one of the course objectives, the final course grade depends to a substantial degree on the ability of the student to communicate the results of his laboratory efforts. The selection of a laboratory course as the vehicle to teach communication skills is particularly appropriate for engineers. The class format is designed to present students with varied requirements which are closely analogous to what they will experience in their professional employment. Perhaps the most important skill learned is the ability to present results and conclusions clearly and concisely in a short written progress report or oral presentation. Rarely will supervisors or, especially, managers have the time for more extensive discussions during the interim status review of individual phases of an overall design project, for example. However, in the final documentation of the design for internal or external distribution, the ability to organize large amounts of data, design calculations and recommendations becomes essential. The major report format is directed toward this objective. Two pedagogical features of this course bear special note. These are the emphasis on rewriting of graded written reports, which is the rule rather than the exception, and the use of tutorial sessions for advance preparation on the oral talks and followup analyses of the written reports. Only through a clear understanding of his deficiencies and extensive practice will the student develop the desired facility in expressing his ideas and describing his achievements. □

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2. For more information contact Ms. Ellen W. Nold, Director, Communications Project, School of Engineering, Stanford University, Stanford, CA 94305.

REVIEW: AMUNDSON

Continued from page 121.

volume contains many examples of Amundson the artist and Amundson the craftsman.

Although a number of the papers in the collection appear in a condensed form in textbooks, the original papers are a preferable source. Many are important references for graduate-level courses in chemical engineering. The polymerization papers with Liu, Warden, Zeman, and Goldstein are, for example, required reading in a course on polymerization reaction engineering. (During my graduate study in 1965, I spent a summer in industry studying and applying these papers to the modeling of a polymerization reactor.) Material in the papers on the single catalyst particle and on tubular and packed bed reactors has permeated most graduate-level courses in chemical reaction engineering and is ideal supplementary reading for students.

At a price of more than $100, the volume unfortunately lies outside the budget of many who would greatly benefit by its presence in their personal libraries. No academic or industrial chemical engineering department should be without at least one copy of this book. For those engaged in or embarking on a career of research that involves the mathematical modeling of chemical engineering systems, the collected wisdom of much of Neal Amundson's incomparable career is well worth the personal investment. □

In Memoriam

LLOYD A. SPIELMAN

Lloyd A. Spielman, 42, Professor of Civil and Chemical Engineering at the University of Delaware, died on March 26 in Newark, DE.

ChE curriculum

TRENDS IN BIOMEDICAL EDUCATION

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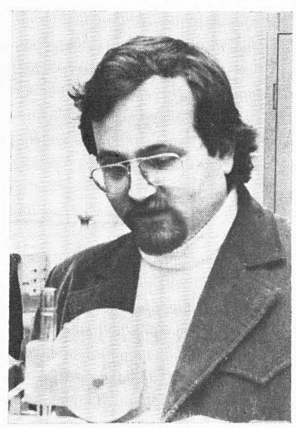
RESULTS OF A RECENTLY conducted survey on Teaching of Biomedical Engineering in Chemical Engineering Departments show that 28 schools out of 79 replying to this questionnaire offer at least one biomedical course for a total of 52 surveyed courses. Most of the courses reported are general in nature although specialized courses in biomedical fluid mechanics, biomedical mass transport, biomaterials and other areas are also taught. Five textbooks and instructors' personal notes cover instructional needs. There does not seem to be any shortage of teaching and research professors in biomedical engineering and the average class size is typical of most elective courses in chemical engineering.

INTRODUCTION

Biomedical engineering can be defined as the application of the principles and practices of engineering to the solution of problems in medical research and health sciences. It was only very recently that this research field was accepted as a viable area of chemical engineering [1, 2], although there are indications of related research activities in the late 50's. In terms of biomedical education in chemical engineering, we have been able to identify a relevant course at M.I.T. as the earliest course of its type offered in a chemical engineering department. It was introduced in the curriculum by Professor Edward W. Merrill during the 1962-63 academic year under the title "Chemical Engineering in Biology and Medicine" and it has been offered regularly since then [3].

Biomedical engineering is considered by many as a "natural" for chemical engineers, since they are qualified to handle problems related to kinetics, fluid mechanics, mass and heat transfer in biological systems and artificial organs, as well as problems related to synthetic materials used in biomedicine. There are strong indications that with the further expansion of major companies in the area of artificial organs, qualified engineers with basic background in the area will be needed.

Those who do not feel that biomedical courses are necessary in chemical engineering point out that there is a very small market for industrial jobs in this area and that even the (rather limited number of) biomedical engineering departments and programs available in certain universities encounter problems in placing their graduates in related jobs. It has also been noted that biomedical engineering is almost exclusively a graduate subject area and that the ratio of research to other industrial positions is rather high. For these reasons, introduction of even one biomedical course in the chemical engineering curriculum is a rather prohibitive "luxury", especially in view of (i) the present popularity of other interdisciplinary areas such as energy, polymers, bio-



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chemical and environmental engineering; (ii) the alarming increase of undergraduate enrollment, and (iii) the considerable teaching load of the faculty, which has not increased proportionally to the enrollments. Finally, unlike other interdisciplinary areas [4], biomedical engineering suffers from an identity problem. The average engineer confuses this area with biochemical engineering. There is confusion, even within the area, due to the development of more medically rather than engineering oriented areas such as clinical and hospital engineering [5].

A recently published British survey/report by White [6] analyzes the research background of some seventy U.S. and Canadian chemical engineers in academic institutions, who are actively involved in biomedical research. Although this report is far from complete, White estimates that there are about 400 chemical engineers involved in medical research in the USA and Canada, excluding those employed by government agencies in peripheral areas such as environmental medicine, etc. Areas of research emphasis include blood rheology and blood coagulation, heat and mass transfer in biological systems, pharmacokinetics, artificial internal and extracorporeal organs, biomaterials, adsorption and separation from biological media, and cardiovascular and respiratory research.

White points out that in the United Kingdom there are no more than 20 academic and a few industrial chemical engineers with biomedical interests. A recent study by the Fédèration Europèene d' Associations Nationales d' Ingenieures (FEANI) [7] does *not* include biomedical engineering as a recommended course in European chemical engineering curricula. In West Germany, the widely accepted "Erlangen alternative" does not include any such courses either in the "Technische Chemie" or in the "Verfahrenstechnik" program [7]. Therefore, it seems that chemical engineering involvement in biomedical research is an "American phenomenon"! It is exercised predominantly in academic research [6, 7] and its impact in chemical engineering is not yet known [9].

BIOMEDICAL ENGINEERING IN CHEMICAL ENGINEERING

Under the sponsorship of the AIChE Educational Projects Committee, a survey was carried out during April 1980 in an effort to analyze the trends of biomedical education, both graduate and undergraduate, within chemical engineering departments. Questionnaires were mailed to 148 departments reported in the AIChE publication "Chemical Engineering Faculties" [10], 135 in the U.S.A. and 13 in Canada. The questionnaires were sent to faculty members previously identified as having research interests in the area of biomedical engineering (about one fourth of the recipients) or to the heads of the departments when such information was not available. A total of 79 responses were received (53.4%) with 74 replies coming from U.S. schools (55.2%) and five from Canadian schools (38.5%).

The main goal of this survey was to obtain and analyze data which would show the trends of biomedical education within chemical engineering. Three types of data were used . . . type and level of course, subjects taught, and textbooks.

Several schools designated that due to the interdisciplinary nature of biomedical engineering, relevant courses are usually taught in other departments. Other respondents noted that in addition to courses offered in chemical engineering, there is a variety of courses in other departments. In processing the questionnaires we had to eliminate a few courses in biochemical engineering, since the coverage of biomedical subjects was not a major part of these courses (less than 30% of the material covered).

Twenty-eight schools offer at least one course in biomedical engineering. It must be noted, that some of these courses are offered at irregular intervals, when there is enough student interest (graduate level), and that, sometimes, a course outline may drastically change depending on the instructor teaching the course. This number corresponds to 35.4% of the responses received or 18.9% of all schools where the questionnaire was mailed. Of those that responded negatively (51), four indicated that they teach some biomedical engineering, six indicated that relevant courses were taught in other departments only and four said that they had discontinued previously offered courses. In addition, five schools stated that they had active research in this area, although no relevant courses.

The survey shows that a total of 40 chemical engineering faculty members are involved in biomedical teaching and 64 are involved in research, for an average of 1.4 and 2.3 faculty members per department respectively. These figures do not include several schools known for their strong bio-

TABLE I
Biomedical Courses Offered in ChE Departments

# COURSES OFFERED	# ChE DEPTS.	%	TOTAL # COURSES		CUMULATIVE %
0	51	64.5	0		
1	13	16.4	13	31	
2	9	11.4	18		59.6
3	4	5.1	12		
4	1*	1.3	4	21	
5	1*	1.3	5		40.4
Total	79	100.0	52		100.0

* These schools offer laboratory experiments in some or all of their courses.

medical program, either because no response was received or because this program is administered by another department (e.g. University of Utah, Case Western Reserve University). For a more accurate picture of biomedical education within chemical engineering we were able to identify through research publications, etc. [11], at least 14 more schools with active biomedical programs which did *not* reply to this questionnaire. Therefore, it can be said with some confidence that at least 42 chemical engineering schools are active in biomedical education and research.

ANALYSIS OF BIOMEDICAL COURSES

The previous analysis is hardly encouraging for the future of biomedical education in chemical engineering departments. As noted earlier, biomedical engineering may be a "luxury" in these days of high enrollments and high faculty teaching loads. To investigate this notion we determined the total numbers of faculty members for the 28 schools that offer a total of 52 biomedical courses. Only six schools from this group have less than ten faculty members, and the average size of a school offering at least one biomedical course is 14 faculty members. The majority of the schools offer one or two courses (Table I). Only six schools (21%) offer 40% of the courses.

Table II shows the number of courses at each educational level. There are 27 predominantly undergraduate (52%) and 25 predominantly graduate courses (48%). Rarities in this list include a freshman general biomedical course (at Washington University) and a sophomore course on mechanics of animal motion (at John Hopkins). All the courses meet at least two hours per week. The only exception is a general biomedical course at Purdue University which carries one credit hour.

A more detailed analysis of the subjects covered in various courses is offered in Tables III and IV. Table III classifies the various courses by area of emphasis according to the course title. There are 29 general biomedical courses (56%). Fluid mechanics and mass transport are major areas of specialized courses. A number of biomedical courses with considerable emphasis on mass transport, but also with additional coverage of other areas were judged by these authors as "general" courses. The area of systems physiology includes courses with significant emphasis on biomedical control. Three courses in biomaterials (at Rice University, C.U.N.Y. and Univ. of Washington) offer the rare case of crossection between two interdisciplinary areas, i.e. biomedical and polymer engineering.

Table IV presents information on subjects covered in the various biomedical courses as provided by the instructors for a total of 46 out of 52 surveyed courses. The cardiovascular and

TABLE II
Educational Level of Biomedical Courses

LEVEL	# OF COURSES	AVERAGE # OF STUDENTS
F	1	25
So	1	12
J	6	19
J/S	3	20
S	11	19
S/G	10	10
G	15	9
All levels	5	30
TOTAL	52	16

pulmonary systems, blood rheology, membrane transport, pharmacokinetics and artificial organs are the most "popular" subjects taught.

Class size and student participation are kept at a reasonable level, typical of most elective chemical engineering courses. The average class had 16 students. The average graduate class had 10 students. The largest classes reported were at Northwestern University for a physiology course (60 students) and at Michigan State University for a general course (40 students).

Chemical engineering faculties include qualified researchers who can teach biomedical

TABLE III
Area of Emphasis and Level of Course

AREA	EDUCATIONAL LEVEL F	So	J	J/S	S	S/G	G	ALL LEVELS	TOTAL
General	1	—	3	2	6	8	7	2	29
Fluid Mechanics	—	—	—	1	—	—	6	1	8
Mass Transport	—	—	—	—	1	1	1	1	4
Systems Physiology	—	—	1	—	1	1	—	—	3
Biomaterials	—	—	—	—	2	—	1	—	3
Physiology	—	—	1	—	—	—	—	1	2
Artificial Organs	—	—	—	—	1	—	—	—	1
Animal Motion	—	1	—	—	—	—	—	—	1
Health Care Technology	—	—	1	—	—	—	—	—	1
TOTAL	1	1	6	3	11	10	15	5	52

courses. Schools reporting the highest number of biomedical researchers were University of Washington (6), Carnegie-Mellon University (5), University of Minnesota (5) and C.U.N.Y. (5).

ANALYSIS OF TEXTBOOK PREFERENCE

Additional information about trends in biomedical education is provided through textbook preference by instructors of the various biomedical courses. A total of 5 books are used as required textbooks in more than one course, while 13 books were mentioned once in this survey (Tables V and VI).

Textbook preferences have been classified in Table V according to the educational level of the course where they were used. These 68 preferences do not represent an equal number of courses, since in certain cases two books (or books *and* notes) were required for a specific course. Perhaps the most significant conclusion drawn from this Table is that the "most cited" textbook was the instructors' "notes".

Cooney's, Lightfoot's and Middleman's textbooks capture 54% of this rather small market. Cooney's textbook is used equally in undergraduate and graduate courses. Middleman's and Lightfoot's books are used predominantly in graduate courses. The only other textbooks with more than one preference were Seagrave's text and Guyton's treatise of medical physiology. Actually Guyton's text is the only one of the five written by a non-ChE. All texts are relatively new, having been published in the seventies. Reference books are rarely used. There is, however, a preference towards supplementary handouts such as review papers etc.

TABLE IV
Areas of Emphasis of 46 Biomedical Courses

AREA	EDUCATIONAL LEVEL F, So, J, J/S, S, all	S/G, G	# OF COURSES
Circulation	16	17	33
Blood Rheology	9	15	24
Membrane Transport	10	13	23
Artificial Kidney	11	11	22
Pulmonary System	10	10	20
Pharmacokinetics	7	13	20
Heart & Lung	8	9	17
Anatomy	8	8	16
Other Artificial Organs	8	7	15
Body Composition	10	4	14
Thermal Effects	4	9	13
Biomedical Polymers	5	6	11
Instrumentation	3	5	8
Physiology	2	2	4
Microcirculation	1	2	3
Others (one or two preferences)	9	10	19

TABLE V
Textbook Preference for 50 Surveyed Biomedical Courses

TEXTBOOK/AUTHOR	EDUCATIONAL LEVEL Undergraduate	S/G, G	TOTAL	PERCENT	
Biomed. Eng. Texts					
Cooney	5	4	9	21.4	
Lightfoot	—	8	8	19.0	
Middleman	2	4	6	14.3	
Seagrave	1	1	2	4.8	
Others (one preference)	3	7	10	23.8	
Other texts					
Guyton	3	1	4	9.6	
Others (one preference)	2	1	3	7.1	
TOTAL	16	26	42	100.0	61.8
Notes	5	15	20		29.4
Literature Handouts	3	3	6		8.8
GRAND TOTAL	24	44	68		100.0

DISCUSSION AND CONCLUSIONS

The main goal of this survey was to obtain and analyze data which would show the trends of biomedical education within chemical engineering. Three types of data were used for this analysis: type and level of course, subjects taught, and textbooks.

The number of chemical engineering departments that offer courses in biomedical engineering is rather small. This subject seems to be of "second priority" in most schools, and it is usually taught as an elective, where there are qualified researchers to teach it. Only two schools of those surveyed offer a biomedical course without having anyone doing research in the area. Although there are several courses for undergraduates only, most of the courses seem to be open to graduate students as well. The authors tend to believe (at least based on the comments in the responses and on the textbooks used) that most of the surveyed courses are of intermediate to advanced level. Courses which are open to juniors must be (by necessity) mostly descriptive in nature, simply because very little mathematical analysis of biological phenomena can be covered if the student has not finished at least one course in transfer/transport phenomena. As far as we know, in most schools, this is done in the junior year.

Based on the analysis of the data of this survey we believe that biomedical engineering has been "accepted" by chemical engineers to the extent that industrial needs warrant it, since the market in this area is rather small. Biomedical engineering may not really be a "luxury", but it is worth noting that most of the schools that offer biomedical courses had rather large faculties. We also believe that this field is research-oriented and it flourishes mostly through work at the graduate level. This does not mean that there are no applications for the subjects taught or researched. However, the market is limited, the competition (from various disciplines) is high, and the results and conclusions of biomedical research are "applicable" mostly to clinical cases (diseases etc.)

TABLE VI
Textbooks Cited for Use in Biomedical Courses (More than One Preference)

AUTHOR	AFFILIATION	TITLE/PUBLISHER
D. O. Cooney	Clarkson College	Biomedical Engineering Principles Dekker, 1976
E. N. Lightfoot	U. Wisconsin	Transport Phenomena and Living Systems Wiley, 1974
S. Middleman	U. Massachusetts	Transport Phenomena in the Cardiovascular System Wiley, 1972
R. C. Seagrave	Iowa S. U.	Biomedical Applications of Heat and Mass Transfer Iowa S.U. Press, 1971
A. C. Guyton	U. Mississippi	Textbook of Medical Physiology Saunders, 1976 (5th ed.)

rather than products. Significant misconceptions concerning the goals of biomedical engineering will have to be addressed by scientific societies.

Most of the biomedical courses offered in chemical engineering are of general nature. They usually include some anatomy and physiology, principles and phenomena related to the cardiovascular and pulmonary systems, pharmacokinetics and artificial organs. Specialized biomedical courses in fluid mechanics, mass transfer and control seem to enjoy some popularity, especially when they address problems related to microcirculation, diffusion in membranes and systems dynamics.

Selection of an appropriate textbook is a rather difficult task. This is not because of the lack of good texts. Actually, in our opinion, all four cited biomedical textbooks are outstanding in their own way. However, biomedical engineering is an area characterized by high individuality in instruction. Since many graduate courses are tailored to the needs of graduate research assistants working in biomedical engineering, emphasis must be placed on one or two specific areas. For example, instructors provided suggestions on additional material that could be covered in a new edition of the present textbooks. These suggestions included: design of artificial organs, thermal physiology applications, more controlled release, more biomaterials, more physiology, more quantitative texts, more and better pharmacokinetics and more thermodynamics.

This simple listing also provides an indication of present and future trends and needs of biomedical education in chemical engineering. It continues to be a predominantly graduate subject. More emphasis is given to quantitative and basic aspects and there is a definite departure from empiricism. "New" areas in biomedical instruction (not necessarily "new" to instructors, but definitely "new" for the textbooks) will have to be added, such as pharmaceutical engineering including controlled release systems, fundamentals of biomaterials, natural membrane science, microcirculation, engineering aspects of cancer research etc.

Class sizes are rather on the low side and some courses are occasionally cancelled due to lack of enough student interest. In recent years, biochemical engineering has entered a flourishing period, mainly due to excellent job opportunities and the development of industrial processes in waste treatment, biomass conversion, other fermentations, food production, etc. However, biomedical engineering is not destined to have a similar role, at least not in the next few years, unless there is a major research and industrial effort towards health problems.

ACKNOWLEDGMENTS

The survey findings were presented at the 73rd Annual AIChE Meeting, Chicago, IL, November 1979. The authors wish to acknowledge the financial assistance of the School of Chemical Engineering of Purdue University in the preparation and distribution of the questionnaires and final reports of this survey. □

APPENDIX

The following is the list of Departments of Chemical Engineering that offer Biomedical Engineering courses and responded to the survey. In parentheses we have designated the researchers who replied. Univ. of Arizona (J. F. Gross), Carnegie-Mellon Univ. (R. K. Jain), Clarkson College (D. O. Cooney), Georgia Tech (A. Yoganathan), Johns Hopkins (S. Corrsin), Univ. of Kansas (K. Himmelstein), Kansas State Univ. (W. P. Walawender), McMaster Univ. (I. A. Feuerstein), Michigan State Univ. (D. K. Anderson), Univ. of Minnesota (K. H. Keller), M.I.T. (C. K. Colton), C.U.N.Y. (H. Weinstein), SUNY Buffalo (P. Stroeve), North Carolina State Univ. (F. M. Richardson), Northwestern Univ. (T. Goldstick), Univ. of Pennsylvania (D. Lauffenberger), Pennsylvania State Univ. (J. Ultman), Univ. Pittsburgh (J. T. Cobb, Jr.), Purdue Univ. (N. A. Peppas), Rice Univ. (L. V. McIntire), Stanford Univ. (C. Robertson), Univ. of Tennessee (W. W. Hsu), Univ. of Texas (R. Popovich), Univ. of Toronto (M. V. Sefton), Tufts Univ. (J. H. Meldon), Washington Univ. (R. E. Sparks), Univ. of Washington (A. S. Hoffman), W. Virginia Univ. (E. V. Cilento), Univ. of Wisconsin (E. N. Lightfoot), and Yale Univ. (C. Horvath).

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Continued on page 143.

RECENT DEVELOPMENTS OF ChE EDUCATION IN MEXICO

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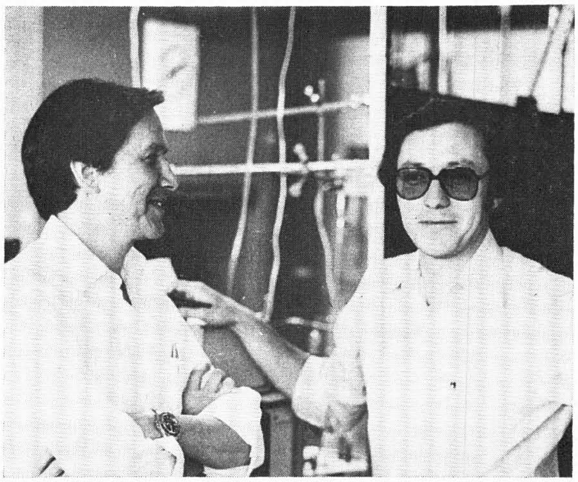
THE CHEMICAL AND PETROCHEMICAL industries in Mexico have had an enormous growth rate during the last three decades (averaging 10-12%/year) and the demand for chemical engineers and other related professionals has grown accordingly. As a matter of fact, from 1973 to 1979 there was an annual increase of 75% in the demand for engineers in these industries.

Because of this demand, the Mexican Government has promoted the establishment of undergraduate programs in chemical engineering all over the country. There are now 54 institutions offering such programs, compared with only half that number six years ago [1]. This has resulted in an explosion of the number of incoming students as well as in those receiving degrees, which oddly enough has exceeded the real demand of chemical engineers by about 25%

This rapid growth has been counterproductive in terms of the quality of the programs offered and of the performance by students and professors. Because of this lack of quality, the larger industries have had to develop training programs to supplement the deficiencies of the new engineers at the beginning of their careers. Also, the most established institutions of higher education have opened graduate programs (M.S. degree only) in order to provide industry with highly qualified engineers, as well as to supply the universities and research institutes with badly needed teachers and scientists. These engineers are beginning to do research and development—activities that, due to the nature of the Mexican industry, were practically non-existent ten years ago [2], and are only now starting to achieve their just dimensions.

The most relevant single event that changed the course of development of Mexican industry was the nationalization of oil resources in 1938 . . . (which) increased the number of chemical enterprises from 379 to 1710.



Enrico N. Martinez, chemical engineer from Universidad Nacional Autonoma de Mexico (UNAM), received his M.S. and Ph.D. (1972) in Chemical Engineering from University of Notre Dame. He was an Assistant Professor at UNAM, and is currently Associate Professor at Universidad Autonoma Metropolitana-Iztapalpa (UAM-I), where he has just been appointed Head of Engineering. He consults in Process Research and Development and his research interests are in Chemical Reaction Engineering, Catalysis and Education. **(L)**

Roman Gomez-Vaillard received his B.Sc. degree in Chemical Engineering at UNAM and his Ph.D. at Imperial College, London. He joined UAM-I in 1976. He has recently become the Chairman of the Chemical Engineering Group there. His research interests are Process Design and Development and Computer Applications in Chemical Engineering. **(R)**

BRIEF HISTORY OF CHEMICAL INDUSTRY IN MEXICO

At this point we will analyze the development of the chemical industry in Mexico, as it has been determinant in the development of the chemical engineering profession and the curricula at the universities that offer undergraduate and graduate programs.

The most relevant single event that changed the course of development of Mexican industry was the nationalization of oil resources in 1938. The resulting growth (from 1940 to 1950) increased the number of chemical enterprises from 379 to 1710. During this period the industry also started to diversify into production of chemical intermediates, pesticides, fertilizers, dies and inks, paints and pharmaceuticals. Employment in the chemical industry rose 13% annually, while it increased by only 6% in the manufacturing industry as a whole. Furthermore, the investment rate had a growth of 25.7% per year versus 10.5% for the manufacturing industry [3].

The Mexican government established control over the petrochemical industry through legislation giving Petroleos Mexicanos (PEMEX) the

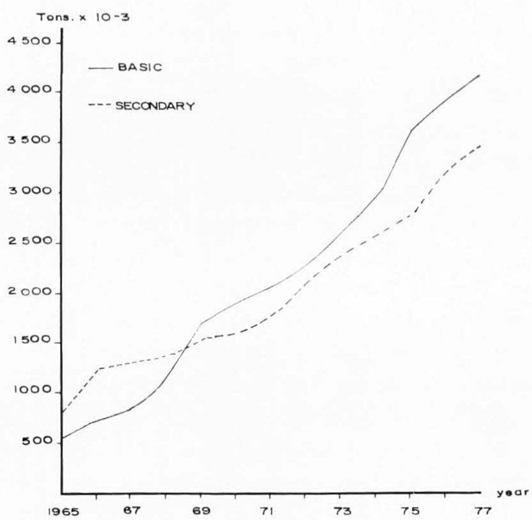


FIGURE 1. Petrochemical Industry: Production

right to produce and/or import all "basic" petrochemicals; "basic" petrochemicals being those products derived through a first transformation of oil and natural gas components. Moreover, private enterprise can use those basic petrochemicals to produce "secondary" petrochemicals if 60% of the share (minimum) corresponds to Mexican capital. Thus, a company fulfilling that requirement can obtain a "Petrochemical Permit" to produce a given secondary petrochemical, such as PVC, phenol, carbon black and other similar products.

An illustration of the development of the petrochemical industry (which by 1975 was already 41% of all basic chemical industry) is shown in Figs. 1, 2, and 3, for the production, imports, and exports of that sector of Mexican industry. All the data were taken from reports by the Mexican

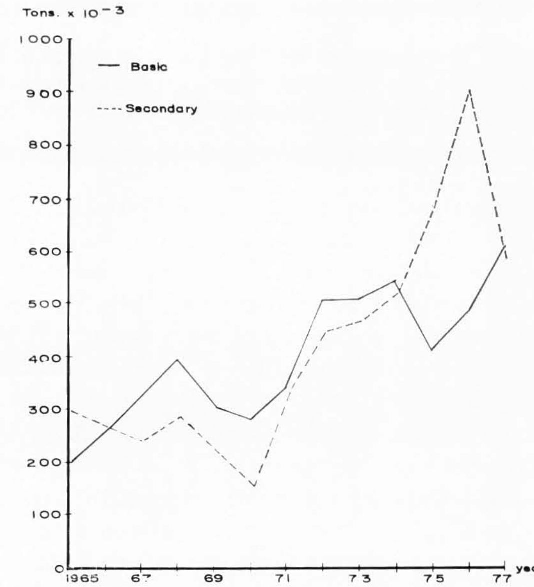


FIGURE 2. Petrochemical Industry: Imports

Petrochemical Commission [4]. It should be pointed out that the deficit in the balance of payments has been growing since 1960, and that most of the equipment and technology for both the petrochemical industry and the chemical industry in Mexico comes from abroad. This fact, as we will see later, has tremendous importance in the development of the chemical engineering profession in the country.

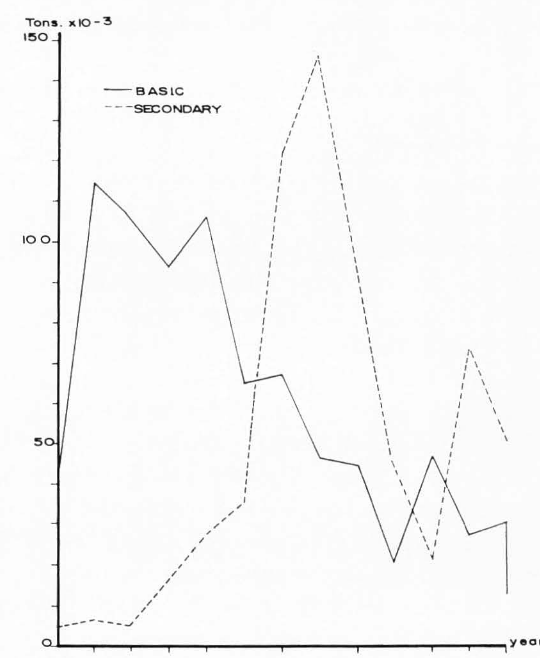


FIGURE 3. Petrochemical Industry: Exports

Because of this demand, the Mexican Government has promoted the establishment of undergraduate programs in chemical engineering all over the country. There are now 54 institutions offering such programs, compared with only half that number six years ago.

The Mexican Government also offered an extraordinary stimulus for creation of the chemical industry in Mexico, with the sole purpose of reducing imports of foreign goods. This policy led, in many cases, to inefficient and expensive production of chemicals, resulting in products that were highly priced internally, with no possibility for export. This situation did not stimulate the development nor the adaptation of technologies, and only required chemical engineers for the operation of plants, the administration of chemical firms and the commercialization of commodities.

At the beginning of the seventies, the government changed its policy in order to reduce foreign debt and to support a healthier industrial development. Emphasis was put on technological independence and the creation of appropriate technologies. The emphasis nowadays is on the creation of enterprises that produce goods at competitive international prices rather than solely for the consumption by the internal Mexican market.

Several facts are indicative of the above; the Mexican Petroleum Institute (IMP) was created in the late sixties with the purpose of performing research and development in oil and petrochemical technology, as well as process and project engineering mainly for PEMEX. The National Council for Science and Technology was founded in 1971; in 1972 the Law of Technology Transfer was published, and in 1973 the Law for the Promotion of Mexican Investment and Regulation of Foreign Investment. Also, a major program for exploration of oil and mineral resources was launched, resulting in the discovery of important oil reserves in Mexico.

Therefore, the challenge faced today by the chemical engineering profession in Mexico is tremendous. As we will see in paragraphs to follow, the curricula of the main institutions have been greatly influenced by the nature of the development and the requirements of industry; but it has not been intended to prepare professionals for the main activities that they perform in developed countries, such as process engineering and research and development. Furthermore, since the most established institutions are slow in changing their programs, new engineers have been educated in sufficient numbers, but at the expense of a loss in quality. A significant lag exists between the real needs of the chemical industry and the supply from the universities [5].

DEVELOPMENT OF CURRICULA IN THE PAST

Since 1940, the demand for chemical engineers has been growing in phase with the chemical industry, and this has produced an explosion of both students and professionals through the years. Fig. 4 shows this situation graphically.

The first institution to offer a chemical engineering degree was the National University (UNAM), starting in 1918. In 1936 the National Polytechnic Institute (IPN) opened the second program in the country. Since then, these two institutions have been the main suppliers of chemical engineers, due mainly to their location in the middle of the densely populated and highly industrialized metropolitan area. Table 1 shows revealing figures in this respect.

Therefore, it is not surprising that the two main schools of chemical engineering (UNAM and IPN) have had a strong influence on the programs and development of most of the schools created later. Actually, most State Universities in the country have been founded by UNAM graduates and their curricula have been, in many cases, the same or very similar to that of the National Uni-

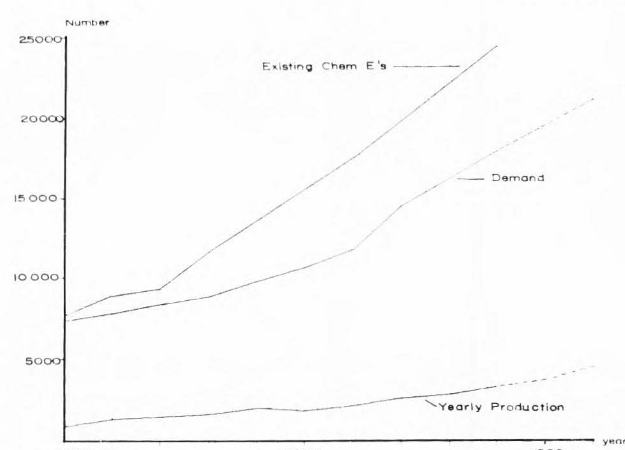


FIGURE 4. Supply and Demand of Chemical Engineers in Mexico

versity. Even the private institutions had exactly the same curriculum from 1943 to 1973. The Ministry of Public Education has opened a good number of Regional Technological Institutes throughout the country in which chemical engineering programs are offered, and these institutes have traditionally followed the programs of IPN.

TABLE 1
Graduates from Chemical Engineering Schools in Mexico (1971-76)

INSTITUTION	NO. OF GRADUATES	%
I.P.N.	6086	35
U.N.A.M.	4560	26
Univ. Aut. de Puebla	1097	6
Univ. de Guadalajara	754	4.25
Univ. Aut. de Nuevo León	546	3
I.T.E.S.M.	480	2.75
All Others	3901	23
Total	17424	100

Therefore, if we analyze the curricula of the two main institutions, we will have a situation representative of the whole country.

The curriculum at UNAM has been shaped according to the needs of Mexican industry and has remained practically unchanged for the last 40 years. The main features are a strong emphasis on chemistry and a wide variety of subjects related to activities that chemical engineers in Mexico have traditionally been involved with, such as aspects of civil, mechanical and electrical engineering. Activities that in developed economies are handled by the respective specialist, but which in Mexico (due to the nature and dimensions of the industry) are given to the chemical engineers to take care of.

Therefore, if we look at the curricula at UNAM and IPN, we notice that they involve a large number of subjects in general, but do not emphasize the fundamental knowledge of basic sciences such as physics and mathematics. Such important disciplines as transport phenomena and process dynamics and control are not a part of the curriculum, but are offered as elective subjects. The same happens with computer programming and numerical methods.

Until 1967, a student had to complete five years of studies in order to get a B.S. in chemical engineering at UNAM; now the program is nine semesters long. At that point, the curriculum was changed from year courses to semester courses, but there was no change in the content. At IPN the program was also five years long and it was only modified to a semester structure in 1975. Also, in order to get a degree, the student had to write a thesis and comply with a Social Service requirement that involves 400 hours of free work as a service to society, since higher education is highly subsidized by the state and is practically costless to the student.

As mentioned in the introductory paragraphs, the number of schools that offer chemical engineering degrees has grown tremendously in the last ten years. Of the present 54, only 9 are private institutions; of these, the most relevant are ITESM at Monterrey and UIA in Mexico City. Both these institutions have contributed significantly to the education of chemical engineers, mainly from the standpoint of quality graduates. In the case of ITESM, its development has been somewhat independent from the large institutions, and in that respect it has pioneered in chemical engineering education, following the patterns of American universities such as Wisconsin. However, as we can see from Table 1, the contribution of ITESM to the supply of chemical engineers amounts to less than 3%.

Another characteristic of undergraduate education in Mexico is that most of the professors teach on a part-time basis and come from industry to teach one or two courses a week. This contrasts with education in developed countries where most of the professors are fully devoted to teaching and research. Table 2 shows figures for some of the most representative schools of chemical engineering.

The government answer to the demand for in-

TABLE 2
Composition of Faculties

INSTITUTION	FACULTY Full Time	Half Time	Part Time
U.N.A.M.	35	8	330
I.P.N.	186	102	142
Univ. Aut. de Puebla	6	18	20
Univ. de Guadalajara	9	—	37
Univ. Aut. de Nuevo León	24	2	47
I.T.E.S.M.	13	1	14
U.I.A.	6	2	12
I.T.R. Celaya	—	—	15
I.T.R. La Laguna	4	3	12
Univ. Veracruzana	10	2	28

creasing numbers of chemical engineers was the creation of a large number of institutions offering the program (22 in the last 6 years). Also, UNAM has opened two new schools in the metropolitan area of Mexico City and, more significantly, the government created the Metropolitan University (UAM) with two campuses offering programs in chemical engineering in Mexico, D.F.

The characteristics of this new university are different from those of other government sponsored universities in several respects. Outstanding are the following facts: there is a tuition fee that is considerably higher than the one charged at UNAM, the academic structure is similar to that of American universities (by departments), and the ratio of students to professors is quite low. In a way, we could say that UAM represents a model of the type of university that the government wants to have in this new stage of development of the Mexican economy.

Thus far, thanks to support from the government, the demand for chemical engineers has been satisfied, in excess, in terms of quantity, as can be seen in Fig. 4. However, the main problem in the last ten years has been quality. According to the opinion of recruiters, only 10% of the graduates have "satisfactory" quality, about 30% are "capable or able to be trained," and 50-60% are "deficient."

GUIDELINES FOR CURRICULUM DEVELOPMENT

The present problem is one of supplying engineers capable of facing the challenge that the development of modern chemical industry poses. Quality should be emphasized, as well as a sound formation in the fundamental principles of chemical engineering that are common to all chemical industries. Also, in order to develop appropriate technologies and to assimilate those imported from abroad, the graduate programs should be strengthened to provide researchers and teachers capable of supporting the proposed new curricula. Therefore, any attempt to develop a curriculum in chemical engineering should be based on two principles:

- **A knowledge of what chemical engineering is, and**
- **A knowledge of the requirements of the chemical industry.**

The first condition seems to be easy to achieve. However, experience has shown that in Mexico most failures in curricula design can be blamed on a lack of knowledge of what chemical engineering is. Although the discipline has reached a great degree of maturity in places like the USA, in Mexico there are very few people with enough background to give a precise definition of the field.

A feasible proposal to solve this problem has been set forth in a previous publication [7]. Basically, this recommendation consists of a definition of those aspects of science that are most important for sound development of chemical engineering, in order to establish a basic structure of knowledge for the first year of the curriculum. Clearly, the fundamental core of any chemical engineering curriculum consists of mass and energy balances, thermodynamics, applied mathematics, transport phenomena and chemical reaction engineering. The basic structure of knowledge should prepare the student to face these disciplines successfully, and should include general physics, general chemistry, and mathematics. All these should have a strong practical support through carefully planned laboratory sessions.

. . . this basic structure of knowledge, as well as the fundamental core, should be established and developed on a national basis through the government sponsored schools.

We believe that this basic structure of knowledge, as well as the fundamental core, should be established and developed on a national basis through the government sponsored schools. In order to do this, an "Academic Commission" should be formed by representatives with high academic standing from each area of the country, calling upon nationally recognized researchers and specialists to work as consultants.

The main purpose of these consultants would be to supply the information needed for the second item of our basic principles; i.e. the requirements of our chemical industry. In this paper, we have given a very brief review of the requirements from our point of view. These have served for the design of the curriculum at our own institution. UAM-I, which we consider to be the model to follow. Therefore in the next section we will deal with it in some detail.

THE PROGRAM AT UAM-I

Fig. 5 shows a schematic of the general activities of a chemical engineer and the interconnec-

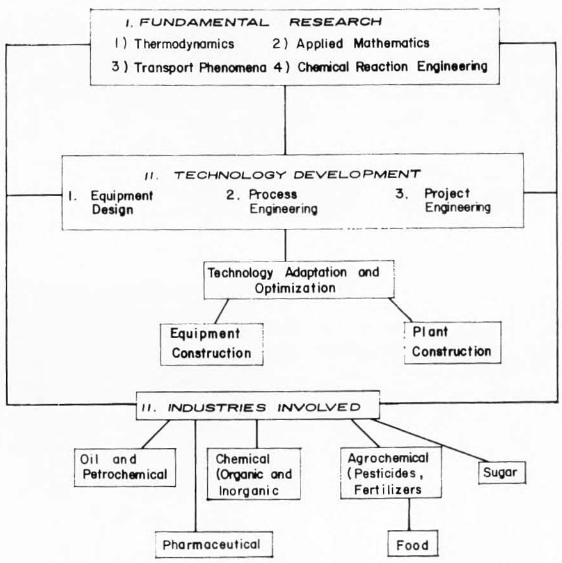


FIGURE 5. General Activities of a Chemical Engineer

tions and relationships with the main industries in Mexico. As can be seen, a wide variety of activities is involved and the industries have large differences among them. Therefore, it is very difficult for a program to attempt to cover every aspect that the future engineer may require, because of the inherent risk of wasting resources and effort. Rather, whatever resources we have can be employed more efficiently if we follow the guidelines given in the previous section of this paper. This would provide a general program with strong chemical engineering fundamentals, flexibility, and adaptability to the different working environments which will confront the engineer.

The objectives of the program at UAM-I are:

- **To educate chemical engineers with a high academic standard, so as to enable them to contribute to the development of the Mexican industry.**
- **To provide the future professional with a strong scientific background that will give him the capability to perform in any given field of chemical engineering, and to solve the inherent problems with the required depth and flexibility.**
- **To provide the future engineer a continuous contact with the problems and needs of the Mexican industry in order to facilitate his finding a role within the context of his future working environment.**
- **To prepare professionals capable of continuing their education in a graduate program, in Mexico or abroad, to strengthen teaching and research in the country.**
- **To prepare professionals with capabilities for developing new and appropriate technologies in accordance with the specific needs of our country.**

Fig. 6 shows a schematic of the curriculum at UAM-I. The foundation of the program is the "General Core" of basic science and engineering. This core is taken by all science and engineering students in the first three quarters at the university. The second stage of the program is a "Common Core of Engineering," which is a group of seven courses in applied mathematics, including computer programming, numerical methods, operations research, optimization and engineering economics. This second core is taken by all engineering students between the fourth and ninth quarters of the curriculum, while they are also taking the fundamental chemical engineering courses.

The last stage of the curriculum is what we call a Major Area, and in particular at UAM-I we offer a major in process design and development. During this stage, the student takes a "Process Design and Development Laboratory," where he is given a comprehensive project with the purpose of developing a technology for manufacturing a product for the Mexican market, under the supervision of our entire faculty. This course is three quarters long and the student is supposed to use bench scale and pilot plant facilities to solve the problems posed by a real project.

The quarter structure of our program leaves room for five elective courses, which should be selected from those offered by other engineering,

Continued on page 143.

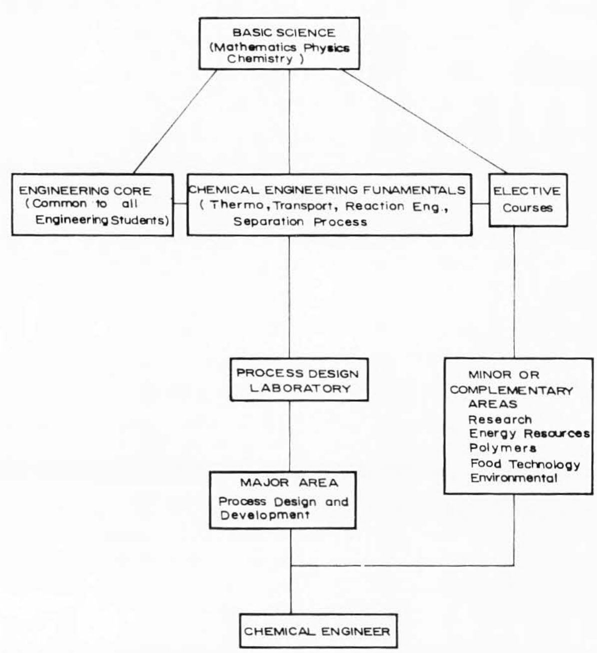


FIGURE 6. Chemical Engineering Curriculum at UAM-I

ChE lecture

CHEMICAL PROCESS SYNTHESIS

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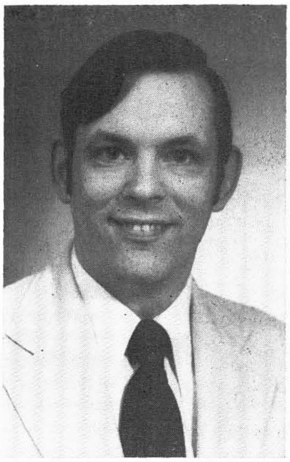
Editor's Note: This is the second installment of Dr. Siirola's two-part lecture. The first installment appeared in Chemical Engineering Education, *Vol. XVI, No. 2, page 68.*



J. J. Siirola received his B.S. from the University of Utah and his Ph.D. from the University of Wisconsin-Madison in 1970 where he developed the AIDES process synthesis system and coauthored the introductory text, **Process Synthesis.** Besides a continuing involvement in synthesis technique development, implementation, and application, his research interests also include simulation and optimization aspects of computer-aided design, non-numeric programming, artificial intelligence, and technology assessment. He is currently a Research Associate in the Eastman Chemicals Division of Eastman Kodak Company.

STATE SPACE SEARCHING

Systematic generation approaches are variants of a problem-solving formalism known as the state space paradigm. Problems framed in this manner consist of an initial state (a set of streams at their initial temperatures or a multicomponent stream to be separated), a set of possible states (streams at intermediate temperatures or streams containing fewer components), a set of possible transformations (changing temperatures by heat transfer or separating multicomponent feeds into two streams of different compositions), descriptions of the states resulting from application of a transformation to a given state (design equations for determining exit temperatures from an exchanger or outlet compositions from a separator), and a final state (the set of streams at their desired temperatures or the set of separated streams). The number of possible states generally increases exponentially with problem size. A solution to the state space problem is any sequence of transformations that leads from the initial state to the final state subject to any constraints that may be applicable. Different paths through the state space may represent the same design. For the heat integration and separations sequencing synthesis problems considered here, the existence of a feasible path from the initial to the final state is usually not in question. Rather, what is sought are paths (designs) which arrive at the final state in some optimal manner.

Since the design that results from a heuristic search often becomes the initial point in an evolutionary structural improvement procedure, it is important that the heuristically developed design be as near to optimal as possible

For sufficiently small problems, it may be possible to search exhaustively through the state space for solutions. Each feasible transformation may be applied to the initial state producing alternative intermediate states, followed by application of transformations to these states generating yet more states, and so on. A search strategy that considers states for transformation application in the same order in which they were generated is termed 'breadth first.' Alternatively, a search strategy can be implemented in which some transformation is applied to the initial state, followed immediately by another transformation applied to the resultant state, and so on. When the final state is reached, alternative transformations are applied to the penultimate state until the final state is again reached. Only after all feasible transformations have been applied to a given state and followed through to the final state are alternative transformations applied to its predecessor, and so on, until all paths through the state space have been generated. This type of search is termed 'blind depth first.' However, if costs can be computed independently for each transformation, the smallest total cost for any complete path generated from initial to final states serves as an upper bound (if minimum cost is the design objective) for other desirable designs. Therefore, for the usual case where costs increase with each transformation, the search can be terminated without reaching the final state if the total cost of a partial path being developed exceeds the current bound.

Ideally, this 'branch-and-bound' technique is more efficient (avoiding a search through more of the feasible state space) if what proved to be the best path is generated early in the search. This might be accomplished by examining at each state all feasible transformations but choosing first the one with lowest cost. Searches which selectively apply state transformations are termed 'ordered depth first.' The technique may be refined by including in the transformation evaluation not only its cost but also an estimate of the costs of all remaining transformations to the final state resulting from its application. This 'predictor ordered search' generally examines the smallest subset of the state space in discovering optimum designs.

In situations where the application of at least some transformations are independent of each other, several different paths through the state space may result in the same design. As this is the case for sharp separations sequencing, it is sometimes more convenient to consider the dual of the usual state space representation in which the transformations become the nodes. This focuses attention on the alternative transformations to be performed rather than on the intermediate states. Each complete and consistent set of transformations joined by arcs of the dual graph represent a unique separations sequence.

Efficient use of state space search in systematic generation synthesis approaches requires at each state the identification of applicable transformations and an evaluation of the value (possibly considering effects on the remainder of the problem) of its application. In the previous examples, and in similar strategies applied to heat integration, as the objective function is taken simply as the sum of the transformation costs, the search is guaranteed to find the optimal design for the classes of transformations available. Searches in this situation have been termed 'algorithmic.'

Chemical process synthesis is an activity concerned with the invention of structurally and operationally superior design alternatives . . . generally performed by experienced, creative engineers assisted by several design aids based primarily on analogy.

However, in many cases involving for example subjective multivariable design criteria, extremely complex transformation evaluations, or very large state spaces, it may not be desirable or even possible to search analytically. The selection or evaluation of transformations can then be made on an empirical basis by using previous experience embodied in design rule-of-thumb. These rules, or 'heuristics,' reflect generally successful strategies, although they carry no guarantees of optimality. Their value is that they often limit the growth of the state space to only a polynomial function of problem size. Heuristic searches are among the oldest systematic process synthesis techniques, having been applied very early to separations selection and sequencing. For this problem, at least 14 such rules are now in common use, including 'remove the most volatile species next', 'remove the species in highest concentration next', 'perform the separation which results in an approximately equimolal split', 'perform separations with high recover fractions last', and 'perform the cheapest separation next.' Similar design heuristics have been proposed for other synthesis subproblems including complex refrigeration cycles and heat integration.

Since the design that results from a heuristic search often becomes the initial point in an evolutionary structural improvement procedure, it is important that the heuristically developed design be as near to optimal as possible. Unfortunately, the advice offered at each state by alternative heuristics is sometimes contradictory. Adaptive heuristic selection procedures can be modified on the basis of the success of repeated heuristic ordered depth first searches. However, for large problems such iteration may not be practical. As an alternative, situation dependent preference ordering of the selection rules has been proposed for once-through heuristic search procedures which terminate when the final state is reached and for guidance in altering the ordering during any subsequent evolutionary modification.

Much synthesis research continues into the search for more powerful design heuristics and more precise definitions of conditions which delimit their applicability. For example, heuristics have been developed which, given only a description of the initial state (and assumed for the final state), completely specify the optimal path without examining the intermediate states for three-component separations that involve simple ordinary and thermally coupled distillation. In heat integration, utility and capital economic factors have led to the realization that better (from a cost criterion) designs generally result from efforts to maximize heat transfer among process streams, while simultaneously minimizing the number of exchangers employed to accomplish it. That maximum integration is consistent with the thermodynamic desirability to minimize network irreversibilities led to a minimum temperature driving force match heuristic. Methods to minimize the number of exchangers have also been investigated. The most significant recent result in heat integration is the fact that maximum integration (and hence minimum utility requirement) and the likely minimum number of exchangers can both be calculated for a given problem before the generation of any networks. This analysis provides additional bounds and targets which can be used to limit the size of the search space, estimate the potential for evolutionary improvement of a candidate design, or estimate the cost of accomplishing heat transfer tasks for a process without actually synthesizing any networks. Similar performance targets, often the result of simplified thermodynamic analysis, are being developed for other synthesis subproblems.

Another critical factor in the application of state space problem-solving approaches in process synthesis is the choice of representation for describing the states and the transformations among them. It is desirable from search efficiency considerations to develop representations which do not include states that cannot possibly be part of the optimal path. On the other hand, care must be exercised so that the experience, prejudice, heuristics, or assumptions embedded into a representation for efficiency do not inadvertently constrain or otherwise exclude truly novel 'creative' optimal solutions from consideration.

COMPLEX SYNTHESIS

Although the previous discussion has drawn examples only from heat integration and separations sequencing, state space systematic generation approaches have also been applied to other synthesis subproblems including reaction paths, control systems, and safety systems. Each of these subproblems is fairly well defined and each has a sizable state space. However, these synthesis subproblems are not necessarily independent. For example, if thermal energy is employed to effect a multicomponent separation as in distillation, the separations sequencing and heat integration subproblems interact closely. The optimal design and operation of a column (operating pressure, degree of feed vaporization, number of stages, reflux ratio, etc.) depend on energy costs and, hence, on heat integration. Heat integration opportunities, however, depend upon column temperatures and heat loads, which are functions of operating pressure and reflux ratio which is, in turn, influenced by pressure effects on the exploited property difference, relative volatility. Further, the identity of the streams available for integration is not known until the complete separation sequence has been generated.

Early procedures for solving this combined problem required excessive effort, largely because of the incompatibility of the dynamic programming approach used for column sequencing with the interactions resulting from heat integration and the large state space of even the restricted integration problem. Later developments in heuristic search improved both the capacity and speed of heat integration syntheses. These improvements allowed all sources and sinks including sensible streams to be considered by an integration procedure fast enough to be included within a design variable optimization of each synthesized separation sequence subject to the same simplifying assumptions. Evaluations of many case studies verified that, although the resultant objective surfaces are very irregular, significant improvements are achieved when designs for these two subproblems are synthesized simultaneously in comparison with independent sequential synthesis. Current efforts, based on the development of improved bounding strategies, seek to generate optimal designs for this combined problem without necessarily generating all paths through the separations sequencing state space.

The design of complete flowsheets is another complex synthesis problem that perhaps embodies all the other synthesis subproblems discussed. Ideally, based on experience with the combined problems of separations sequencing and heat integration, it may be desirable to solve all the subproblems simultaneously. Development of such a formulation is a formidable task and may never be accomplished. Several simplified approaches, however, have been suggested.

One scheme, like other systematic generation approaches, decomposes the problem in such a way that at least one task is immediately recognizable as achievable with available technology such as a reactor, distillation column, or heat exchanger. Given descriptions of the desired product, potential raw materials, pertinent chemistry, and available technology, the binary resolution procedure of predicate calculus was adapted to prove constructively the existence of a path through the state space. Since for most real design problems the existence of a solution is not in question, resolution was replaced with a goal-directed depth first search (proceeding backwards from the desired products) followed by evolutionary improvements involving recycles and energy recovery to generate efficient overall designs.

Alternatively, a decomposition scheme is possible that does not result in the immediate recognition of available technology but rather a multilevel series of subproblems similar to the synthesis subproblems identified previously. The innermost level subproblem involves the selection of chemical transformations by which available raw materials are to be converted into the desired product. Once approximate conversions and yields of the chosen reactions are determined, a rough material balance can be calculated. In the next subproblem, the fate of each chemical species in every raw material and reactor effluent is assigned. Decisions to recycle unconverted reactants, remove contaminants before or after reaction, allow them in the product, send them to waste treatment, or process them into byproducts, etc. are made. The implementation of this species allocation is addressed in the next subproblem by using means-ends analysis to detect required temperature-changing, pressure-changing, stream-splitting, species-separating and or other physical transformation tasks. The outermost level subproblem specifies processing equipment and control strategies to effect the required tasks, integrating as appropriate consecutive or complementary tasks for capital and operating cost efficiencies. Each of these subproblems interact. Correct reaction choices depend upon how the reaction path will be implemented. Optimal species allocation to support the reaction path depends in part upon the separation problems which arise as a result of the allocation. The selection of physical transformation tasks and their operating conditions may depend upon the degree of task integration, etc. At each level, choices are made as a result of an analysis of the bounds defined by actions taken in previous levels and by heuristic estimates of the probable effects of the choice selected on subsequent levels.

STATE OF THE ART

The level of sophistication exhibited by the systematic chemical process synthesis techniques so far developed ranges from primitive to moderate. From an industrial point of view, heat integration synthesis is the most mature, although no single technique is universally superior in all applications. The prediction of utility bounds, minimum number of exchangers, and identification of evolutionary structural improvements are significant design tools. Some computer programs are commercially available. Heat-integrated separations sequencing also has industrial applicability, although at present is somewhat limited by simplifying assumptions. The total flowsheet synthesis computer programs are strictly experimental. It is, of course, not necessary that successful process synthesis techniques be computerized, although in research the development of computer implementations sometimes forces more careful attention to logic detail.

Industrial interest in continued progress in process synthesis techniques is strong. Well-attended symposia sponsored by AIChE and others throughout the world are becoming more frequent and serve as a forum for discussion of latest results. Current research needs include relaxing the restrictive assumptions particularly related to type and component distribution in separations sequencing techniques and developing improved representations to account for phase equilibria and possibly reactions occurring within separations equipment. Additional work is needed in the development of complex synthesis strategies and of heuristic transformation selection and evaluation functions for efficient state space searches which avoid unnecessary prejudice or constraints. Improved performance targets and bounding properties will be required for search space reduction and dual-level design optimizations. Also work needs to continue on combined synthesis problems such as control strategies and heat integration.

As more difficult synthesis problems are examined, more problem-solving techniques may be required for their solution. Although the goal of chemical process synthesis research is definitely not the computerization of the design invention activity, some powerful paradigms have been developed within the computer science discipline of artificial intelligence. For example, pattern recognition and semantic information processing were once considered as a means for coding and retrieving the historical experience of the profession for application to new problems, but were abandoned because of the feeling that novel, creative solutions were unlikely. Likewise, theorem proving was the foundation of resolution based flowsheet synthesis but was ultimately rejected when structural optimization rather than proof of feasible design existence was sought. Learning techniques were incorporated into heuristic transformation selection functions and goal-directed state space search techniques. It is expected that these and other artificial intelligence strategies such as planning, reasoning, and game playing may be an important part of the solution procedure for more difficult synthesis problems.

Finally, synthesis is a fundamental part of the synthesis-analysis-evaluation-optimization process design activity. Although once the exclusive domain of the experienced practitioner, the results of the research reviewed here indicate that at least some concepts such as decomposition and state space search can be formalized. And as such, it seems definitely desirable to incorporate these as well as some of the specific procedures for selected subproblems such as heat integration, separations selection and sequencing, or control systems along with discussions of concept discovery aids and descriptive chemical engineering into traditional design courses. In less detailed form, basic synthesis concepts would seem to be an excellent introduction to the nature of chemical engineering, providing an overview and foundation for the rest of the curriculum.

CONCLUSIONS

Chemical process synthesis is an activity concerned with the invention of structurally and operationally superior design alternatives. This activity has generally been performed by experienced, creative engineers assisted by several design aids based primarily on analogy.

Several approaches not necessarily patterned after existing concept discovery practice have been proposed for systematic process synthesis. Optimization approaches attempt to apply traditional mathematical methods for operations optimization to structural optimization. Evolutionary approaches identify features for possible modification or rearrangement. These approaches require some preinvented design. This invention can be accomplished with decomposition or systematic generation approaches. Perhaps a truly competent process synthesizer should contain elements of all three approaches.

Systematic generation involves decomposition and a subsequent search through very large state spaces. For some synthesis subproblems, these searches have become tractable through the development of efficient state representations, search heuristics, and bounds on the state space containing optimal designs.

Industrially significant results have been obtained in the area of heat integration. Other useful techniques have been demonstrated in reaction path selection, separations sequencing (particularly combined with heat integration), control systems, and complete flowsheets. Traditional concept discovery aids and newer systematic synthesis approaches should be included in process design instruction.

Significant research opportunities remain, particularly in the area of combined synthesis subproblems. Solution techniques for more difficult problems may require greater application of artificial intelligence techniques. Tradeoffs between level of detail and search efficiency will be difficult and representation and heuristic search developments must be made carefully to avoid unnecessary or unintentional constraints. □

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ChE EDUCATION IN MEXICO

Continued from page 137.

or related, programs to form a coherent complementary, or minor, area. All students must spend one summer in industry in a regular job after their junior year, and they must also comply with the Social Service requirement mentioned previously. However, in contrast with other programs, there is no thesis requirement for graduation.

At this point, we should mention that similar programs have been proposed at UNAM, but are still pending approval for their implementation [8]. Also, private insittutions (such as UIA) are already operating with a curriculum whose basic philosophy coincides with ours, but with differences in the form of implementations. This is due to the fact that their faculty is fundamentally part-time, whereas at UAM-I most of the faculty is on a full time basis. This brings up the point that, in order for any program to be successful, the level of preparation of the faculty members should be the highest possible, and the composition must be shifted from primarily part-time to mostly full time teachers. It is in this respect that the graduate programs in Mexico have become increasingly important, and therefore should be strengthened.

CONCLUSION

A brief review of the development of chemical industry and of the chemical engineering profession in Mexico shows that they have been in phase in terms of supplying the quantity of engineers required by industry. However, quality has been a problem, particularly in the last five years.

Mexican industry now requires a different type of chemical engineer; one capable of assimilating the imported technologies and developing new processes more suitable for the efficient utilization of our resources.

We propose the formation of an "Academic Commission" on a national level, formed by highly qualified professors from all parts of the country, in order to coordinate the design of a curriculum which could be implemented at all government sponsored schools. This curriculum should contain a fundamental core of basic science with a strong interaction with practice through lab sessions. The second stage of the curriculum must emphasize the fundamentals of chemical engineering and, finally, the third stage can be flexible and concentrate on several aspects, depending on the region of the country or the strength of the faculty at hand.

It is obvious that the implementation of the proposed curriculum requires highly trained teachers and researchers. These people should be prepared through the graduate programs now existing in Mexico. Such programs must be strengthened and should be strongly supported at the main government sponsored institutions. An overview of graduate education in Mexico will be published in a later issue of *Chemical Engineering Education*. □

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BIOMEDICAL EDUCATION

Continued from page 131.

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C. O. BENNETT

Continued from page 101.

semester; one for seniors and one for graduate students. These tend to be more mathematically oriented. "The graduate courses are always pleasant because I usually get quite a few questions from the students and we have good discussions. But there is a lot to cover, so I wind up talking quite a bit," he says.

Bennett's teaching has had great influence around the world, since he has taught students on four continents—North and South America, Africa, and Europe. His first overseas teaching venture (at the University of Nancy in France) came in 1952, and reflected the influence of his continued love of the French language and culture that developed in his high-school and Yale days.

During his first visit to Nancy, Bennett helped form that university's chemical engineering department, according to one of his French colleagues, who added, "Having Prof. Bennett with us was extremely valuable. We benefited from his American experience and he gave us good advice on organizing courses and problems, on establishing laboratory experiments, as well as on the construction of buildings, and above all, the unit operations laboratory." During another visit to France in 1970-71, Bennett participated in research at Nancy on the design of catalytic reactors, and "made important contributions in the conceptual design of laboratory reactors," according to a colleague there, who also believes Bennett played a role in developing chemical engineering throughout France. He goes on to say, "Thanks to his perfect knowledge of the French language, Bennett has many times been consulted by academic authorities and even national ministries concerning important decisions in the domain of chemical engineering. Prof. Bennett's advice has always been heeded and followed." It is not surprising that the Bennett and Myers textbook is one of the basic books used by French chemical engineering students.

France also called to him during his 1977 sabbatical year, which he spent at the University of Lyon. At Lyon he worked as a laboratory researcher, read a great deal, and got to work with some of the leaders in the field of catalysis, many of whom were at Lyon. "I learned a lot there, and it helped me quite a bit, and influenced my career, too." Bennett reflects. He still maintains a cooperative research relationship with the University of Lyon, and exchanges transatlantic visits with some of its researchers.

Bennett's other extended foreign involvement was with a country in a quite different situation, Chile. He spent a period in 1964 at the University of Santa Maria in Valparaiso (under an Agency for International Development contract), returned there in 1972 as an Organization of American States lecturer, and last visited there in 1979. Thus he was in a position to watch that country's descent into turmoil, from the apparent normality observed on his first visit.

Bennett's teaching visit to Vienna, was shorter, only about a month in 1971. He also made two trips to Algeria, where he taught natural gas processing.

At home Bennett finds pleasure in many things other than his work. Besides being a "gourmet eater" (his son Johnathan is a professional chef), Bennett also enjoys classical music and art. He started playing piano at the age of eight and can play Scott Joplin rags, "ineptly" he claims. Otherwise, his tastes run more to Mozart, Beethoven, and Brahms. His interest in architecture and art now has professional guidance, since he married a UConn art professor and Egyptologist, Jean Keith, two years after his first wife, Elizabeth Jane Balch, died. Bennett and Keith were married August 24, 1979, on the anniversary of the eruption of Mt. Vesuvius, which buried the Roman city of Pompeii in 79 A.D., "a date quite suitable for us," Bennett notes. □

REVIEW: FLUID FLOW

Continued from page 108.

engineering or returning to it. In its area of coverage, this book is more convenient to use and more comprehensive than the handbooks and it has the very great advantage of the worked-out example problems. The references, if not last minute, are at least solid and extensive. And I can also recommend the book for the faculty member called upon to teach design classes to have on his desk as a handy reference. The comprehensive problems given at the end of each chapter will also be useful to the faculty member.

In summary, this is a solid contribution to the chemical engineering literature, even if it does not suggest itself as a vital component of the undergraduate curriculum. I am certainly pleased to have a copy where I can reach for it. □

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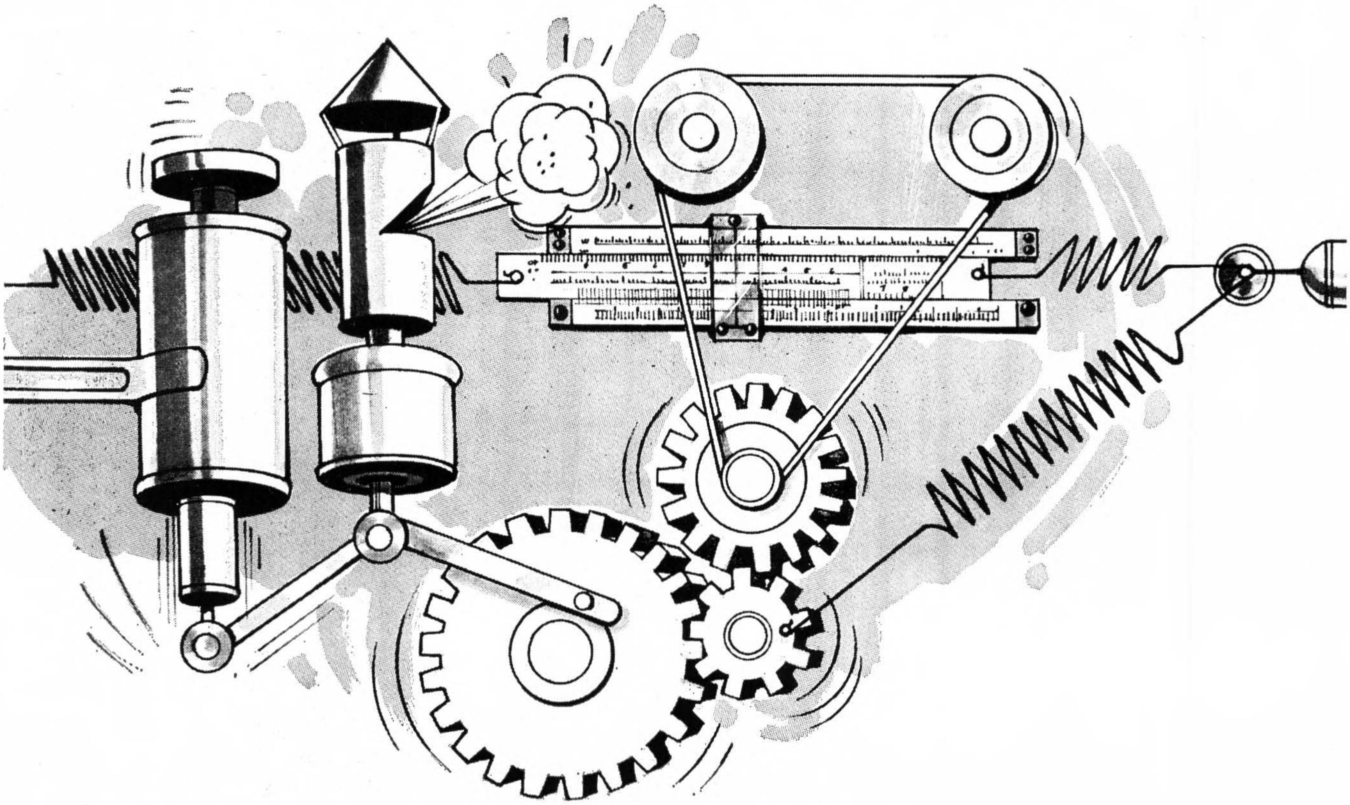

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