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CHEMICAL ENGINEERING DIVISION OF AMERICAN SOCIETY FOR ENGINEERING EDUCATION

Lee C. Eagleton
of
Penn State

CHEMICAL ENGINEERING IN THE FUTURE
SCIANCE

THE INDUSTRIALIZATION OF A GRADUATE
RHINEHART

MICROCOMPUTER-AIDED CONTROL SYSTEMS DESIGN
ROAT, MELSHEIMER

SIMPLIFYING CHEMICAL REACTOR DESIGN BY USING MOLAR QUANTITIES
BROWN, FALCONER

CHEMICAL REACTION EXPERIMENT FOR UNDERGRAD LAB
KWON, VAHDAT, AYERS

CHE EDUCATION AND PROBLEMS IN NIGERIA
OKORAFOR

A PROBLEM WITH COYOTES
YOUNG

CHE AT
MANHATTAN COLLEGE

CEE

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Lee C. Eagleton

of Penn State

ROBERT L. KABEL
Pennsylvania State University
University Park, PA 16802

THIS ARTICLE SHOULD be titled "Tennis, Chemical Engineering, and Tropical Fish (In That Order)," but these articles don't have titles.

Lee Eagleton had just arrived as the new department head at Penn State, and to get acquainted he scheduled in-depth interviews with all the members of the chemical engineering faculty. One senior professor felt that his interview was going well. He was providing profound insights, and Lee seemed receptive. The interview was nearing its climax when Lee said, "I have to play tennis in five minutes." The professor was stunned . . . and Lee was gone. Lee explained sometime later that if you don't put tennis first, it ends up last.

In 1978, John Tarbell wrote in *CEE* that "when Dr. Eagleton first arrived on campus in 1970, he was shocked to find that no one on the faculty played tennis (Lee was seventh man on the tennis team at MIT one year, but never won a match). As a perceptive administrator, he quickly recognized this deficiency and soon convinced Dr. Danner (an assistant professor at the time) that tennis might be an important component of his professional development. Ron was obliging and served admirably as a partner until he received tenure, at which point his tennis enthusiasm suddenly waned. This situation was alarming and an exhaustive search for new talent was undertaken. Fortunately, Dr. Duda (whose background in polymer science was surpassed only by his twenty years of tennis experience) was looking for an academic position at that time. Larry and his wife were conveniently lured away from Dow Chemical Company to complete a formidable mixed doubles opponent for the Eagletons."

Eagleton earned bachelor's and master's degrees from M.I.T. and the DEng from Yale, where he performed his doctoral research under the supervision of Harding Bliss. The article resulting from his thesis was cited by George Burnet as a landmark publication. After five years as a development engineer with Rohm & Haas, Lee joined the faculty of the University of Pennsylvania and was there for fifteen years until his move to Penn State. His research at Penn focused on vaporization of liquids, kinetics of catalytic processes, and reactor design, for which he was cited in being named AIChE Fellow. He was an acknowledged expert on the effect of mixing on chemical reactions and regularly lectured and chaired sessions in this area. Stuart Churchill credits Lee as being one of those who was primarily responsible for the upward turn in quality and reputation of their university's chemical engineering program. Stu writes, "Indeed, we have never really accepted his departure, and have always treated him as an unofficial member of our department."

. . . to get acquainted [Lee] scheduled in-depth interviews with all [faculty members] . . . The interview was nearing its climax when Lee said, "I have to play tennis in five minutes." The professor was stunned—and Lee was gone. Lee explained . . . that if you don't put tennis first, it ends up last.

Thus it was that Lee Eagleton brought his "Ivy League" outlook to this Central Pennsylvania outpost in 1970. We needed him. His unique, urbane style made a difference in issues broad and small. An example of the small occurred when electronic calculators became available. The College of Engineering Executive Committee was stampeding toward banning them from use in examinations when Lee mused aloud as to whether the college should establish such an anti-technological policy. The stampede was headed off and a ludicrous action was avoided.

A broad issue greeted Lee when he arrived at Penn State. Chemical engineering was perceived externally as being totally focused on petroleum processing and irrelevant in modern times. The perception was exaggerated, but it is true that at that time one-half of the faculty of fourteen did *no* teaching. Within two years, two of those seven had retired at age sixty-five, and the rest were in the classroom. Lee encouraged the research programs of the young faculty who had been carrying the bulk of the teaching load, and he supported the enhancement of the best of the hydrocarbon related research. He carried out this transformation, which could have led to rebellion, with diplomacy and *savoir faire*.

One of Lee's great pleasures is mingling with the leaders of any discipline. He turned this inclination to our great advantage by bringing in many of the biggest names in chemical engineering from around the country and the world, as much to expose the Penn State faculty to their perspectives as to acquaint the visitors with the departmental renaissance. Those visitors and our faculty were regularly invited to his home. Lee's style was to direct the actions of his wife, Mary, and his children, Bill, Jim, and Beth, this way and that for the benefit of his guests. His generalship, and their good-natured acceptance of it, was really part of the entertainmment.

The real stars of his show were two, almost wall-sized, salt-water aquaria. Lee caught the tropical fish himself in the Caribbean waters near his vacation home on St. John. The fish would grow to several inches in length and often lived to ripe old ages under his care. Lee used his reaction kinetics expertise to develop an ultraviolet sterilization technique for the circulating salt water, to protect the fish from fungi and other problems. In every major city (*after* playing tennis and attending the AIChE meeting) Lee would seek out the curator of the local aquarium to share information on the care of salt-water tropical fish. He even published an article on his UV sterilization method. His very famous coauthor was Earl Herald, curator of the Steinhart Aquarium.

Lee's fascination with highly talented people was also crucial as he initiated a faculty recruiting program which was to achieve great success. To illustrate, he attracted Larry Duda, Jim Vrentas, Al Vannice, and Fred Helfferich to Penn State. All of them had significant industrial experience, obvious creativity, and an inclination to fundamental research, factors which have since led each of them to national awards.

Lee and Mary relaxing over breakfast in the Caribbean.

At the same time as Lee's departmental research revolution was coming into its own, the enrollment explosion struck. He saw it as an opportunity for growth and as a way to gain increased faculty and financial resources for the department. He encouraged creative responses to the problems of advising and teaching of vastly larger numbers of students. His research on faculty workload measurement, published in 1977 in *CEE*, was crucial in balancing responsibilities during that stressful time.

The thirteen years (1970-1983) that he led our department were difficult years for the whole university and especially so for the College of Engineering. For chemical engineering to have experienced such growth and improvement in quality during an era of retrenchment and deterioration elsewhere on campus must be attributed to Lee's leadership.

Beyond leadership, Lee Eagleton has perfected the art of procrastination. The scientific foundation

He has been heavily involved in the Summer Schools and has held all offices in the ChE Division. He volunteered to serve on the *CEE* Publication Board and was Secretary of the Division when *CEE* was moved to the University of Florida. He was elected Publication Board Chairman in 1981, where he served through 1985.

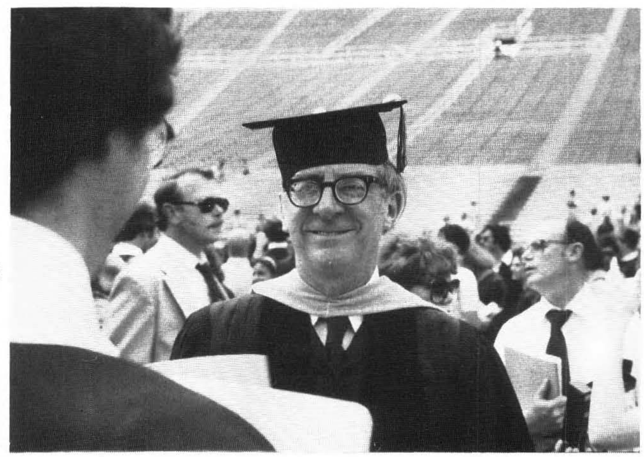
Lee and Mary pose with friend and primary tennis partner at Penn, Stu Churchill.

for his practice is, "If you put something off long enough, the need for it may disappear." The result is that those things which don't disappear receive his attention *after* the last minute. Thus, procrastination has led him to idiosyncratic efficiencies. Those of us who have traveled with Lee to local AIChE meetings recall him dictating responses to a backlog of correspondence in the din of a crowded automobile. One faculty member in the know says that Lee's administrative assistant would have candidates for department secretarial positions transcribe such dictation to see if they were immune to discouragement.

Another such example of Lee's "efficiency" is his use of his HP-41C programmable calculator. Lee, Larry Duda, and Bill Steele, of Chemistry, were walking over to the tennis courts a few hours before Lee was to meet his class. When they were almost there, Lee reached into his pocket, pulled out the calculator which had been working a problem the whole time, wrote down the answer, and went on to play tennis.

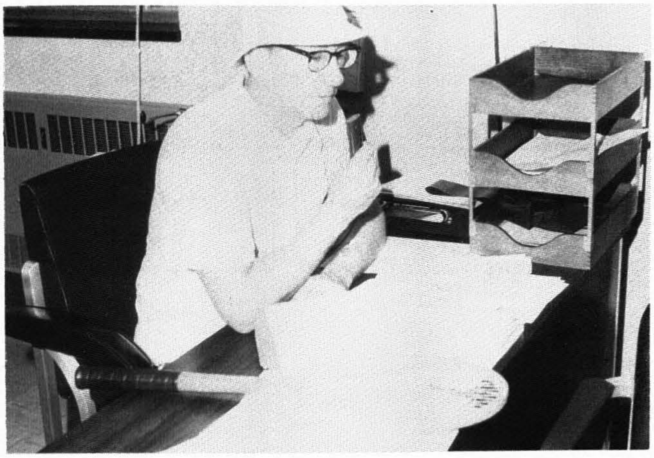
Lee is an active member of AIChE at all levels. Students have always found him to be an enthusiastic supporter of their organization, and his good nature has made him the perfect foil for their humor at banquets and other gatherings through the years. He could always be counted on for an extemporaneous Jack Benny-type monologue at graduate seminars, retirement parties, or other functions. What could not be anticipated was his topic or the perspective he would bring to it. In any lineup of speakers, no one ever wanted to follow Eagleton's act.

In 1983 the Central Pennsylvania Section recognized Lee Eagleton's contributions to the section and beyond by giving him the AIChE Diamond Jubilee Award. At the national level he served a three-year term as director and was chairman of the committee on AIChE Dynamic Objective 4. This was the objective that outlined changes in educational programs which would prepare chemical engineers for the increasing complexity and diversity of the profession and which reemphasized the applications of chemistry as the distinguishing feature of chemical engineering. Lee was also active on the Education and Accreditation Committee. His work on Dynamic Objective 4 led the E&A committee to consider the liberalization of accreditation requirements for chemical engineering programs. This evolution continues today. An E&A colleague, Dee Barker, pointed out that of the large AIChE membership, only fifteen people comprise this important body. Of those only three or four are members of the ABET Engineering Accreditation Commission. The fact that Lee serves on the ABET EAC is indicative of the high degree of confidence chemical engineering people have in him.



Lee at 1981 graduation, sharing a final word with one of his students.

One might wonder what special talent makes Lee invaluable in such roles. Consider that he is the all-time memo champ. The successive energy shocks of the middle 1970's brought about widespread and appropriate attention to conservation, as well as some overzealous if well-intended efforts. Penn State was no exception, and its energy czar was Ralph E. Zilly, who inundated us with energy bulletins. Some of them were inane, and Lee referred to them as "silly Zillies."



A bit of dictation before heading for the courts.

In a memo of March 4, 1975, Zilly banned the use of portable electric heaters by secretaries. This aroused the competitive fire and wit of Eagleton and led to his masterpiece of March 14, 1975, which was termed a "Zilly dilly" by our appreciative secretaries. Nevertheless the battle between these two persistent memo-masters (REZ humorless, LCE wry) raged on for almost two years until, on January 4, 1977, Zilly caved in with, "Your point is well taken." Space requirements preclude the inclusion of their memorable correspondence in this article; however, copies of key memos will be provided by the author upon request. This anecdote may seem frivolous, but it illustrates Lee's determination, his disarming wit, and his tolerance of diverse opinions, all of which make him so effective in deliberative bodies.

Although he had numerous opportunities (Deanships, National ASEE, *etc*) to expand his field of influence, Lee consistently chose to focus his energies on his professional discipline. For example, he was recently elected to the select group of ASEE Fellows. His election was, however, almost entirely because of his activity in the Chemical Engineering Division. He has been heavily involved in the Summer Schools and has held all offices in the ChE Division. He volunteered to serve on the *CEE* Publication Board and was Secretary of the Division when *CEE* was moved to the University of Florida. He was elected as Publication Board Chairman in 1981, where he served through 1985. Klaus Timmerhaus credits Lee with pushing hard to make *CEE* the quality publication that it is and for helping to set up the mechanism for adequately financing its operation.

All three of Lee and Mary's children followed his example by studying engineering. Beth is an industrial engineer with Rockwell International in Los Angeles. Jim most closely fits the mold with chemical engineering degrees from Michigan and MIT, a job with Rohm & Haas in Philadelphia, and involvement in a recent AIChE contest problem. Bill's current position as a cook for Stouffer's Restaurant in King of Prussia seems to go back more to his catering service at his father's receptions than to his college education.

When you see Mary, ask her about Lee's devotion to the evening tennis doubles group. The group was surprised one night when a substitute, Jack Purnell, showed up for the 8 o'clock game. Jack (who still plays with the group) is an anesthesiologist at the local hospital where Lee was preparing for minor surgery. Lee was on the table, ready for the mask, being wheeled by the anesthesiologist to the operating room, when he said, "Wait a minute, I have to play tennis tonight." □

ChE letters

HOUGEN MEMORIAL

Editor:

I just wanted to drop you a note and thank you for initiating the tribute to the memory of Olaf Hougen in your journal. I think that the finished product is quite fine, and I have already heard a number of favorable comments. I hope that some of the material in the summary will be interesting to many of your readers and that through the "Hougen Principles" his influence will spread still further.

R. B. Bird
University of Wisconsin

ChE book reviews

ECONOMIC EVALUATION IN THE CHEMICAL PROCESS INDUSTRIES

by Oliver Axtell, James M. Robertson
Wiley-Interscience, Somerset, NJ 08873 (1986), 241 pages, $44.95.

Reviewed by
Max S. Peters
University of Colorado

This short book presents a general treatment of methods used for economic evaluation in the chemical process industries with primary emphasis on keeping the presentation as simple as possible. There are essentially no mathematical equations in the entire book, and quantitative analysis is limited to examples

Continued on page 33.

Overview of the Manhattan College campus.

ChE department

MANHATTAN COLLEGE

CONRAD T. BURRIS
Manhattan College
Bronx, NY 10471

THE YEAR 1987 marks the one hundred thirty-fourth anniversary of the founding of Manhattan College as a private independent college under the sponsorship of the Brothers of the Christian Schools (Christian Brothers). Although originally a commuter school for New York City students, the college's 4500 students now come from 17 states and 53 foreign countries. The largest division, the School of Engineering with 1500 students, was established in 1896 with programs in civil engineering and electrical engineering. Curricula in mechanical engineering and chemical engineering were introduced in 1957 and in 1958, respectively.

Although possessing the name "Manhattan," the college is located in Riverdale, an attractive residential section of New York City in the northwest corner of the Bronx on the heights overlooking Van Cortlandt Park. The campus was previously located on the island of Manhattan where the name originated, but moved to its present location in the Bronx in 1924. Since it already had an established reputation at the time of the move there was no effort to change the name along with the location.

Chemical engineering was introduced along with mechanical engineering at a time when a new engineering building was planned for the campus. As part of the planning process, advisory groups of industrial consultors were organized to meet with administrative officers to provide input so that the new departments would reflect the latest thinking of the engineering profession. With the assistance of the members of the Chemical Engineering Consultor Committee, a program was initiated at the sophomore level in 1958. The first enrollees were chemistry majors who decided to take advantage of the new opportunity presented to them. The first class graduated in 1961.

UNDERGRADUATE PROGRAM

The program began with very little in the way of equipment although a recently acquired building near the campus was available for its use. The industrial advisors who provided the incentive to get the program underway now came to the rescue. The chairman of the Consultor Committee, who was then a vice president of a major corporation but who had previously served as chairman of a chemical engineering department in an academic institution, realizing the needs of a new department with limited resources and knowing how industry could help, provided the necessary assistance. He assigned an engineer from his company to visit several chemical engineering schools to determine what experiments were needed for a modern unit operations laboratory and then authorized him to visit the company's storage locations to select appropriate surplus equipment which could be used in an academic environment. A laboratory manual was prepared based on the donated equipment so that a full set of experiments was ready for the first senior class.

Since that time the department has continued to expand, with modern laboratory equipment having replaced the donated surplus equipment. Today's unit operations laboratory is in excellent condition, thanks to grants from several companies and government agencies. Recent equipment grants from the National Science Foundation are providing opportunities for further updating of our undergraduate laboratories. Reverse osmosis and ultrafiltration, along with experiments in biotechnology, will now become an integral part of our undergraduate laboratory offerings.

The department has had three chairmen during its short history. Brother Conrad Burris served as chairman during the early years of the program. He was succeeded by Jack Famularo who served for four years and Joe Reynolds who served as chairman for seven years. Brother Burris, after serving ten years as Dean of Engineering, returned to the chemical engineering department and was again appointed chairman.

Close faculty-student interaction characterizes the Manhattan College program in chemical engineering. Small class size and excellent library and computer facilities in the Engineering Building and a newly constructed Research and Learning Center provide an excellent environment for the learning process. A special feature of our program is the involvement of undergraduate students in the research activities of the faculty. Among the research projects involving undergraduate student participation are the following: fluidized bed studies; analysis of air pollution control systems; hazardous waste incineration; paint and colloid surface phenomena; protein separation and purification processes; industrial wastewater treatment and membrane mass transfer studies. Many of these students are co-authors of published papers and papers presented at professional society meetings. In the last five years twelve papers involving student authors have been presented at meetings or conferences and nine journal articles have been published or accepted for publication.

Computer terminal room in the new Research and Learning Center.

Although primarily an undergraduate institution, Manhattan College has a chapter of Sigma Xi, which is somewhat unique since chapters of this prestigious research honor society are usually associated with doctoral granting institutions. Over the past five years, seventeen undergraduate students from the chemical engineering department have been inducted into the Manhattan College chapter.

Chemical engineering graduates from the Manhattan College program have done well in both graduate schools and in industry. In the past five years, 27 of the department's graduates have obtained or are in the process of obtaining their doctorate degrees from a variety of prestigious graduate schools. In addition, 82 graduates have obtained master's degrees. Several graduates each year also enter medical, dental and law schools. Chemical engineers from Manhattan College are highly regarded professionals in industry, with many achieving high-level positions in major chemical, petroleum, pharmaceutical and design companies.

DESIGN-ORIENTED MASTER'S PROGRAM

Once the undergraduate program was established and accredited, consideration was given to developing

. . . Manhattan College, following the advice of its industrial advisors, decided to introduce a design-oriented master's degree program as an alternative for those students whose career objectives were directed toward design, production, and management rather than to teaching or research.

a graduate level program. At the time this was being considered in the mid-sixties, circumstances were such that there was no need for another doctoral granting institution in the New York City area. The college's industrial advisors were of the opinion that there were more than enough research-trained engineers with masters and doctorate degrees. Much of the graduate research done during that period was highly theoretical and geared to the programs being supported with federal funds. The needs of the more traditional chemical industries for engineers with some application-oriented work at the graduate level was becoming increasingly evident.

At that time it was noted that there were many talented sudents who desired advanced training in engineering, but who had little interest in research. These students were entering research-oriented programs because there were no alternatives available to them. The conclusion was that a need existed for a graduate program in engineering practice. This program was planned with the objective of training and motivating students toward productive careers in industry, and terminating at the master's degree level. New York City already had several engineering schools with excellent research-oriented graduate programs in chemical engineering, so Manhattan College, following the advice of its industrial advisors, decided to introduce a design-oriented master's degree program as an alternative for those students whose career objectives were directed toward design, production, and management rather than to teaching or research. The program was termed "design-oriented" because process and plant design project work is employed in place of a research thesis. The projects require exercise of judgment, creativity, and sound economic reasoning, and thus prepare a student for a wide spectrum of engineering assignments in industry. Although design had become an integral part of undergraduate chemical engineering education, its role at the graduate level had been minimal.

Several approaches to the program were considered by the faculty in consultation with their industrial advisors. It was generally agreed that some meaningful involvement by industry should be an integral part of the program. The MIT Practice School model was considered but discarded as being too expensive and impractical for an institution such as Manhattan College. In addition, industry appeared reluctant to support additional programs of that type. It was finally agreed that a three month "Summer Phase" should precede a nine month "Academic Phase." The summer phase would be under the direction of a "participating company" which supported the program. The company agreed to provide a work experience in the design office, laboratory, or plant which would be relevant to the overall objectives of the program. During this period a faculty representative from the chemical engineering department would monitor the progress of the student by visits to the industrial site. Selection of the student for specific summer jobs would be handled cooperatively by the college and the company involved, and salary, working conditions, and related matters would be handled by the company. Because of the proprietary nature of much of the work done during the summer months, it was agreed that the summer project should not be continued during the academic phase as part of the process and plant design project.

Required courses during the academic phase include applied process thermodynamics, distillation, design of thermal systems, and chemical reactor design. Included among the available elective courses are advanced chemical engineering economics, engineering statistics, numerical methods and computer methodology, optimization techniques, and computer methods in process simulation. In general, graduate courses are taught by faculty members whose background includes appropriate industrial experience. Adjunct faculty are also utilized to take advantage of their particular specialties. The many industries in the New York metropolitan area provide an excellent source of part-time teachers.

The specific objectives of the process and plant design project are to develop the capabilities of the student in the area of process synthesis, technical and economic evaluation of alternatives, process optimization and communication skills. Overall, student reaction to the project has been extremely favorable. Students have found it to be the unifying element within their graduate education. This is not as much due to the fact that the project represents the culmination of the program as it is to the fact that it serves to bring together much of the knowledge previously held to be unique and isolated.

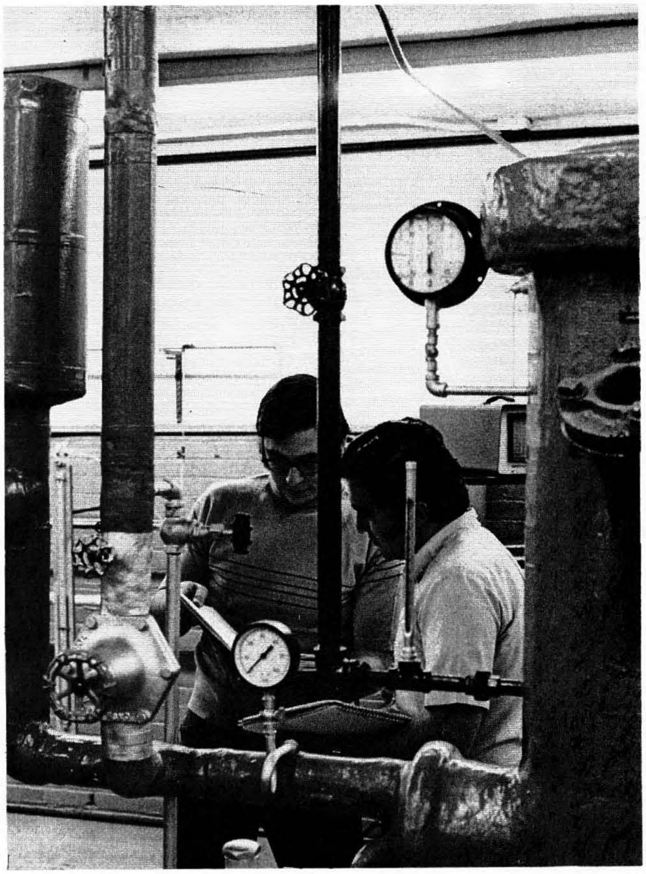
Industry involvement continues during the academic phase of the program. A steering committee made up of members of the faculty and a representative from each of the participating companies meets once or twice during the year to review the program and to make recommendations for its improvement. In addition, the participating companies provide seminar speakers who give appropriate up-to-date information on industrial topics. Recent seminar topics have been: Three Dimensional Plant Design on a CAD System; Application of Unit Operations in Cryogenic Air Separation; Hazard and Risk Analysis of Process Systems; and Hazardous Waste Management in the Petroleum Refining Industry.

This program has been in operation since 1967 with the participation and support of such companies as Air Products & Chemicals, Inc., Celanese Plastics Company, Lummus Crest Inc., Exxon Corporation, FMC Corporation, Mobil Oil Corporation, Stauffer Chemical Company, Texaco Inc., Pfizer Inc., Consolidated Edison Company of New York, and Union Carbide Corporation. Reports from those companies employing graduates from the program indicate that it has been particularly effective in improving the competence of young engineers by affording them an intensive, guided experience in developing their capabilities in handling industrial problems. Over 450 master's degrees have been granted since the program began twenty years ago.

EXTENSION TO LATIN AMERICA

Once the program became successfully established in the United States, it was expanded to include applicants from Latin America. It was believed that this type of educational opportunity would be of greater benefit to many Latin American students seeking an advanced degree in chemical engineering than the more traditional "research-oriented" program. This is particularly true if the student's career objectives are directed towards production and management. In general, programs of this type are not yet available in Latin America.

On the advice of Manhattan College's committee of chemical engineering advisors from industry, contact was made with representatives of government agencies, industry, and educational institutions in several Latin American countries. There was general agreement with the objectives of the program, and an effort was made to cooperate with industries and academic institutions in those countries by providing interested students from a cooperating engineering school with summer employment in the plant, design office, or laboratory of a participating company in the Latin American country in which the program was to become operative. After completion of the summer industrial phase, the student would spend the academic year at Manhattan College before returning to the



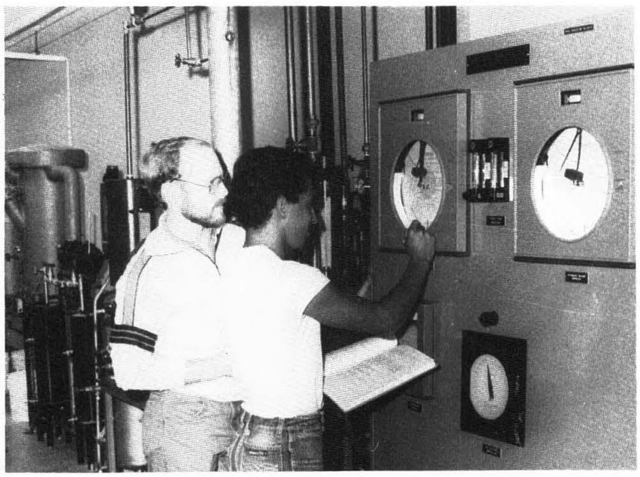
Students comparing notes in the unit operations lab.

country of origin. It was hoped that industry would provide financial assistance for those participating in the program.

Although there was general agreement with the value of the program, the format found to be successful in the United States was not viable in Latin America. Cooperation between industry and education in Latin America appears to be less than it is in the United States, and where it does exist there is little enthusiasm on the part of academic institutions involved to use industry support to provide scholarship assistance for local students to study abroad. They believe that local industry support should be for local academic institutions. So, while there was some willingness on the part of industry to provide suitable employment to satisfy the "summer phase" of the program, complications associated with the selection of a student acceptable to the company and monitoring his performance made this procedure impractical.

Since the "summer phase," or prior industrial experience, was felt to be important, a more suitable model for students from developing countries was sought. Fortunately, close cooperation with Bufete Industrial, a Mexican owned design and construction company, helped provide a suitable model for maximizing the advantages which the program provides. The "summer phase" has been replaced for the Bufete candidates with six months to two years of industrial experience as employees of the company. They are then, in general, better prepared to appreciate the opportunities which the program provides than their United States counterparts. Students accepted for the program are employees of the Process Development Department of Bufete Industrial, so have been exposed to an appropriate industrial environment.

The Latin American extension of the program has been particularly successful in Mexico, with over 50 students completing the program. An additional 25 students from several other Latin American countries have completed the program and returned to their countries. The recent decline in the price of oil, which has had an adverse effect on the economies of several Latin American countries, has resulted in a decrease in applicants from that part of the world.



Collecting data for the distillation experiment.

OTHER GRADUATE PROGRAM OPTIONS

Although the original "Design-Oriented" Master's Degree Program was planned for full-time students, it became apparent that young engineers working in the chemical industry in the New York metropolitan area could also benefit from this type of program. Since they were already engaged in engineering work, the need for a design project as part of their degree requirement was considered unnecessary, so a part-time evening program consisting of the four required courses and six elective courses was established.

During the period when chemical engineers were in short supply, many chemists wished to work for the master's degree in chemical engineering. In order to accommodate these potential applicants, a "Chemist's Program" was established leading to the Master's Degree. Although they had a strong background in chemistry, these candidates lacked a background in chemical engineering. As a result, they were required to take and successfully complete twelve credits in undergraduate chemical engineering courses before being allowed to matriculate in the graduate program. Over 65 chemists have successfully completed this program in the nine years that it has been in operation.

PARTICULATE SOLID RESEARCH, INC. (PSRI)

Although not formally a part of the chemical engineering department, this organization (established in 1970) provides an opportunity for faculty and student involvement in applied research of benefit to the industrial community. The laboratories of PSRI are adjacent to the Manhattan College campus. The Technical Director, Fred Zenz, was originally attracted to Manhattan College because of its "Design-Oriented" graduate program. His recognized competence in the area of fluid-particle technology led to an institute devoted to the development of design data for use by industry. PSRI is modeled after the two older research institutes, Heat Transfer Research Institute (HTRI) and Fractionation Research Institute (FRI). A wide variety of useful information has been generated by this organization under Fred Zenz's leadership. Current investigations by this group include dilute phase conveying, dense phase conveying, cyclone efficiency and particle attrition. These studies have led to the development of basic formulations demonstrating that the properties of fluid-solids systems are analogous to liquid-vapor systems and obey the same quantitative relationships.

FACULTY ACTIVITIES

Continuing the tradition of excellence in teaching chemical engineering, the faculty is constantly upgrading course offerings to keep pace with advances in technology. Several of the faculty have been instrumental in developing new courses. Helen Hollein has introduced courses in biochemical engineering at both the undergraduate and graduate levels. Stewart Slater's contribution includes two new courses; one in separation techniques for resource recovery and a second in membrane process technology. Louis Theodore, who has been teaching graduate courses in air pollution control for many years, has recently developed a new course in hazardous waste incineration.

Although the department's Master's Degree Program is still "design-oriented," some experimental work involving the newer technologies is underway. A recent NSF equipment grant has enabled Stewart Slater to develop a laboratory devoted to modern separation techniques such as reverse osmosis and ultrafiltration. Helen Hollein, also with the assistance of a NSF equipment grant, is establishing a laboratory in biotechnology. Both of these laboratories will be devoted to undergraduate instruction, undergraduate and graduate research participation, and faculty research.

Jack Famularo has been actively involved in updating our unit operations laboratory by incorporating computers into several experiments. These include a computer-controlled heat exchanger experiment and experiments in unsteady-state conduction and distillation. In addition he is currently doing research involving studies of adsorption processes in water treatment systems.

Helen Hollein is currently conducting research involving experimental studies and mathematical models for protein adsorption and desorption in ion-exchange chromatography. She is also working on the development of new resins for preparative separation of biological molecules by high-performance liquid chromatography. Stewart Slater's research in reverse osmosis is directed at process modeling and industrial wastewater treatment. He has developed models to simulate different processing modes based on mass transfer and operational parameters and is currently modeling the effects of concentration polarization. Helen Hollein and Stewart Slater have joint research projects on the purification and concentration of biological mixtures by ultrafiltration processes.

Louis Theodore and Joseph Reynolds are currently working in the area of air pollution and hazardous waste disposal by incineration. Their activities nicely complement the water pollution emphasis of Manhattan College's well-established environmental engineering program.

In addition to his work as Technical Director of Particulate Solid Research, Inc., Fred Zenz handles the design component of the undergraduate program as well as several of the graduate courses in the "design-oriented" master's degree program. Paul Marnell, who had many years of industrial experience, handles the graduate program design projects.

The recent opening of a Research and Learning Center on the Manhattan College campus is providing the much needed space for the expanding interests of the chemical engineering department. The future looks promising. □

ChE lecture

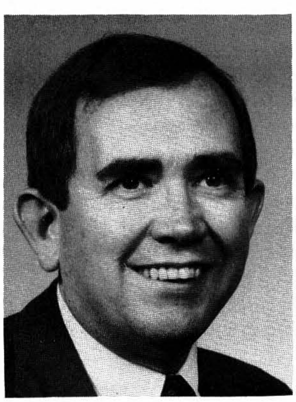
CHEMICAL ENGINEERING IN THE FUTURE*

C. T. SCIANCE
E.I. Du Pont de Nemours and Company
Wilmington, DE 19898

CHEMICAL ENGINEERING AND its future direction are important and interesting subjects to those of us in the profession. There is much to talk about. In this paper we discuss three aspects of the future of chemical engineering. The first concerns change: What evidence is there that the profession of chemical engineering needs to evolve? And why are these changes taking place?

The second part addresses the needs and expectations of industry, or at least that segment of it which is likely to employ chemical engineers: What do we need and expect from our new engineers? What role do we expect chemical engineers to play, and what could that role be if their training were different?

The perspective presented is largely a personal one. Each company, and each division or even each individual within a company, sees things differently. But since each of you know many people from industry, you can judge these opinions in the larger context. Certainly the members of the Septenary Committee on the Future of Chemical Engineering, sponsored by the University of Texas at Austin, represented a wide spectrum of companies employing chemical engineers; yet they were in remarkable agreement about many issues.



C. Thomas Sciance received his BS (1960), his MChE (1964) and his PhD (1966) from the University of Oklahoma. He served in the U.S. Army during 1961-62 and joined Du Pont in 1966 as a research engineer. Since November 1983, he has been Director of Engineering Research in Du Pont's Engineering Research and Development Division. He is responsible for research done by Du Pont's Engineering Physics and Engineering Technology Laboratories, both located at the Experimental Station near Wilmington, DE.

The first concerns change: What evidence is there that the profession of chemical engineering needs to evolve? And why are these changes taking place?

The third part suggests possible courses of action. Some would involve only the academic community. Others would require the participation of professional societies such as the ASEE or AIChE; organizations such as the Chemical Research Council that bring together academic, government, and industry representatives; government funding agencies such as the National Science Foundation; textbook publishing houses; or individual firms that employ chemical engineers.

The real issue is cohesive leadership. There are signs that the need for change is recognized, and at least some elements of the matrix are willing to be persuaded to change. Leadership involves setting directions and priorities and providing incentives for movement in the desired direction.

SIGNS OF CHANGE

The Du Pont Company is a large employer of engineers, especially chemical engineers. Surveys have shown that chemical engineering students think of Du Pont as one of the best places to work. Therefore, changes taking place in Du Pont should be of interest to suppliers of chemical engineering students. Allow me, then, to cite several examples that impact upon the recruitment and careers of chemical engineers.

The Engineering Technology Laboratory, established in 1929 in the Chemical Engineering Group of Du Pont's Central Chemical Department, has been a continuing major influence in the field of chemical engineering research. It was a thrill for me as a chemical

*"Tutorial Lecture" for ASEE Chemical Engineering Division: June 23, 1986; Cincinnati, OH.

TABLE 1
Engineers in Du Pont

Final Degrees as of 1/1/86

	BS	MS	PhD	Total	%
Chemical	2911	768	504	4183	45
Mechanical	2066	361	82	2509	27
Electrical	898	127	21	1046	11
Other	1057	353	105	1515	16
Total	6932	1609	712	9253	
Percent	75	17	8		

engineer to lead a research organization founded by Thomas Chilton.

The Chemical Engineering Group grew from two people in 1929 to 37 in 1953. Many employees such as James Carberry, Allan Colburn, Thomas Drew, Robert Marshall, and Robert Pigford have become well-known in the field. The chemical engineering section of the lab has traditionally been a leader in industrial chemical engineering.

Since May 1 of 1986, however, there is no longer a Chemical Engineering Section *per se* in the Engineering Technology Laboratory. The groups have been renamed to reflect a focus on technologies of corporate strategic significance. The new names? Bioengineering. Electronics Materials Engineering. Structural Ceramics. Electronics Ceramics. Polymer Processing and Compounding. Composites and Applied Mechanics. Membranes Engineering.

In the meantime, the tiny Applied Physics Section, founded in 1945, has become the Engineering Physics Laboratory, equal in size to its sister Engineering Technology Laboratory. It is divided into two main sections (Applied Physics, and Electronics and Optics) but within those areas there is a substantial and growing emphasis on materials science. Development of electro-optic devices, characterization of composites, work on optical-disk storage devices, and the modification of materials by microwave radiation are all fields that might have a chemical engineering aspect but are presently the province of solid state physicists and materials scientists.

What's in a name? A lot. Names help focus direction. Names inspire loyalty and *esprit de corps*. If you are looking for signs of change, do not ignore changes in the names of organizations, groups, or functions.

You should find this alarming. A shift of emphasis in industrial research indicates a trend in future jobs in manufacturing and marketing. To industry, it matters little whether applied physicists or chemical engineers are doing the work. If chemical engineers are to be hired, they must receive the training that will make their expected contributions greater than those expected from other disciplines.

Recruitment Trends

Another clear indication of change for the field of chemical engineering can be seen in Du Pont's recruitment trends. Du Pont is a highly diversified company that employs a great many chemical engineers. As shown in Table 1, Du Pont (minus Conoco) employs about 16,000 people with college technical degrees, out of a total exempt force of 22,000. More than 9,000 of these are engineers, of whom 45% are chemical engineers. In all, 25% of the engineers hold advanced degrees, as do 30% of the chemical engineers.

Since [last] May . . . there is no longer a Chemical Engineering Section *per se* in the Engineering Technology Laboratory. The groups have been renamed to reflect a focus on technologies of corporate strategic significance.

During the past ten years, we have hired 2,242 chemical engineers, half of the total number of engineers hired. Although individual years vary a great deal, some trends are clear. Figure 1 shows that the relative percentage of chemical engineers hired has dropped.

Specific figures are listed in Table 2. In the three-year period 1976-79, Du Pont hired 746 chemical engineers, 52% of the total number of engineers hired. Of these, 5% of the chemical engineers had PhD's. In the three-year period 1983-86, seven years later, 373 chemical engineers were hired, 43% of the total. Of

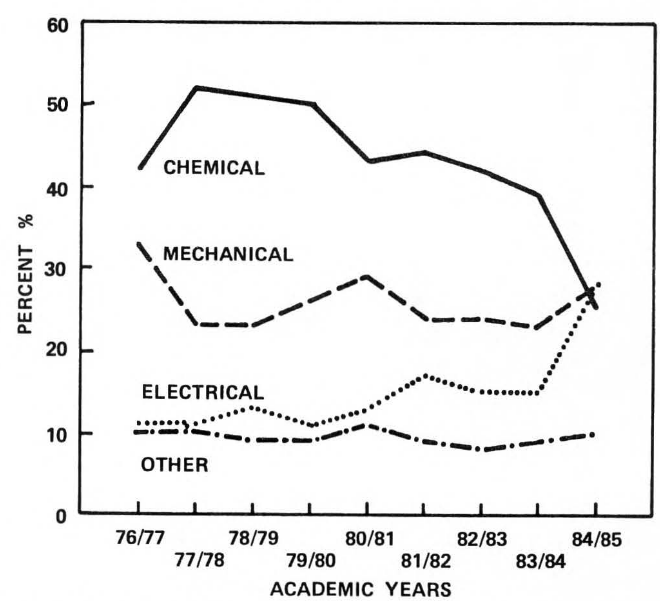


FIGURE 1. Ten-Year history: Du Pont engineering hiring for Bachelors and Masters degrees

these, 21% had the PhD. In this seven-year period, the total number of chemical engineers hired dropped by half, and the percentage of PhD's among them quadrupled. The absolute number of PhD hires in chemical engineering increased by 114 in the face of a 58% decline in BS/MS hires. The trend toward hiring fewer chemical engineers who individually know more seems unmistakable.

Other types of engineers are faring relatively better. Subtracting these figures will show that, although

TABLE 2
Chemical Engineering Recruitment

	CHEMICAL ENGINEERS			ALL ENGINEERS		
	B-M	PhD	Total	B-M	PhD	Total
1976-79	710	36	746	1383	60	1443
1983-86	296	77	373	763	102	865
Change, %	–58	+114	–50	–45	+70	–40

the total number of BS/MS hired dropped 45%, this figure represents a 58% reduction in chemical engineers combined with a 31% reduction in all other types of engineers.

Consider electrical engineers, not shown specifically in Table 2. We employ over 1,000, 11% of our total engineering employment. Comparing the same periods, Du Pont went from 172 hired to 182, a 6% rise in the face of a drop of 40% in the total number of engineers hired. The very small number of PhD's doubled from 4 to 8, but the latter figure would have been higher had we been more successful in recruiting them. One of our problems in recruiting is that, as a chemical company, we are not yet perceived by research-oriented EE's to offer outstanding opportunities for them. We are trying to combat this erroneous perception.

A number of our R&D positions are being filled with applied physicists and materials science and ceramics majors. Again, we are pleased with the quality of these people, but to the field of chemical engineering such hires may represent lost opportunities. Unless something is done to change the trend, the role of chemical engineers in industry will diminish. Also, it seems that the part of industry which hires chemical engineers will gradually move away from having the BS as the terminal degree. This happened with chemistry, biology and mathematics long ago. These trends have major implications for those who teach chemical engineers.

Market Orientation

Everyone pays lip service to market and customer orientation. In fact, since the publication of *In Search of Excellence* [1], not to do so would be heresy. Those who have seen such trends come and go develop a certain degree of cynicism about them. However, we believe that the movement toward better customer orientation, both in Du Pont and the chemical industry in general, is truly significant and has long-term implications for the field of chemical engineering.

We compete in an international market where other countries have equivalent technical skills and infrastructure, plus advantages such as labor cost. Where formerly we might have expected a sustainable cost and hence price advantage through technology alone, now we must focus on providing value to the customer not merely by lower price but in every way that the customer sees value. Examples of change in Du Pont include not only formation of new, customer-oriented entities but also new ways of thinking about existing organizations. Consider the new organization chart for our Biomedical Products Department, shown in Figure 2.

Instead of the traditional triangle with the Group Vice President at the top, here you see the various divisions clustered like flower petals about the health-

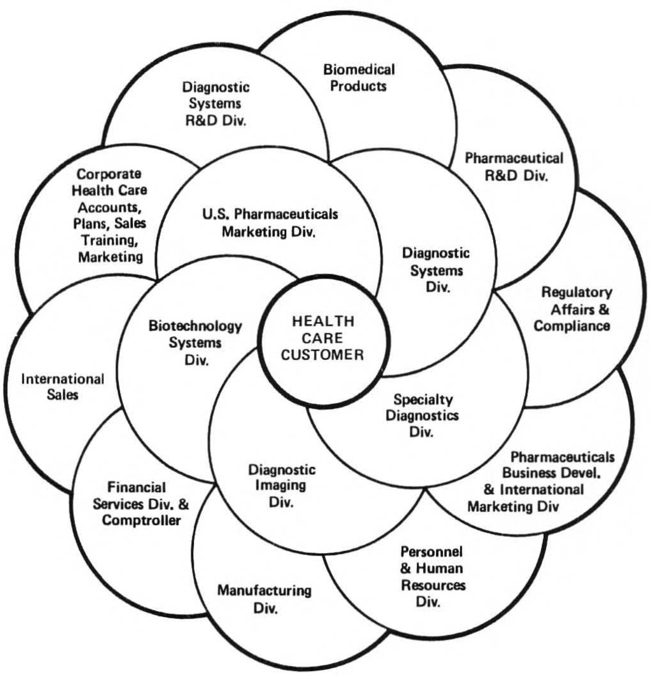


FIGURE 2. Organization chart

care customer. Note also that the names of the divisions—pharmaceuticals, diagnostic imaging, biotechnology systems, specialty diagnostics, etc—differ considerably from such traditional areas as nylon, polyethylene, and industrial chemicals.

Although our Engineering Research organization has no outside customers, we do have a well-defined internal market. Our clients are Du Pont's other departments. We receive about one-third of our funds from the corporation for long-range and discretionary R&D, and must get the other two-thirds by convincing our clients that we can serve them better than someone else can. They are free to go elsewhere.

Table 3 lists some of the ways in which recent trends affect the practice of chemical engineering.

TABLE 3
Recent Trends Affecting ChE's

- **MOVE OF BASIC INDUSTRIES OFF-SHORE**
- **FLEXIBLE MANUFACTURING**
  - **Automation**
  - **Batch Processes**
  - **Small Scale / Small Lots**
  - **Rapid Changes**
- **PRIMARY EMPHASIS ON QUALITY, SERVICE, VALUE-IN-USE RATHER THAN PRODUCTION PROCESS AND TECHNOLOGY**

While this change in emphasis is relatively recent for much of the chemical industry, the focus on customer needs is well-established in the electronics industry, which is now hiring more chemical engineers.

Traditionally, chemical engineers have found positions in the chemical and petroleum industries in jobs emphasizing the scaleup of processes. The six-tenths power factor "proved" that technical work oriented towards ever-increasing scale would be rewarded many times over. After all, half again as much investment would build a plant producing twice as much. Not many people noticed that in some cases the 0.6 factor was becoming 0.7, 0.8 or even higher, and that the effort and expense directed toward keeping huge plants on-line were beginning to outweigh the vaunted advantage of scale. Technical efforts were directed toward ever-increasing reliability to counter the extremely high cost incurred when the unit was shut down for any reason.

Next, problems arising from cyclical swings in the economy were found to be accentuated by the enormous single-line plants whose breakeven rates were 70% of design or higher. During an economic downturn, a producer with two small plants could shut one down, doing relatively well by running the remaining unit efficiently. To the large producer, the laws of economic thermodynamics (you can't win—you can't break even—you can't quit playing) were not so funny, as they found themselves forced by contracts and internal needs to continue playing a losing game.

Also, it seems that the part of industry which hires ChE's will gradually move away from having the BS as the terminal degree. This happened with chemistry, biology and mathematics long ago.

Another blow to the concept of unalloyed benefits from ever-larger scale came with the realization that real value to the customer might lie in small amounts of material tailored to the customer's needs, as opposed to huge amounts tailored to the producer's desires. Considerable technical effort was devoted to "product wheels" or other schemes to make large plants behave more like small ones. The effort to be flexible and maintain high quality while tailoring products to each customer is a dominant theme in process work today.

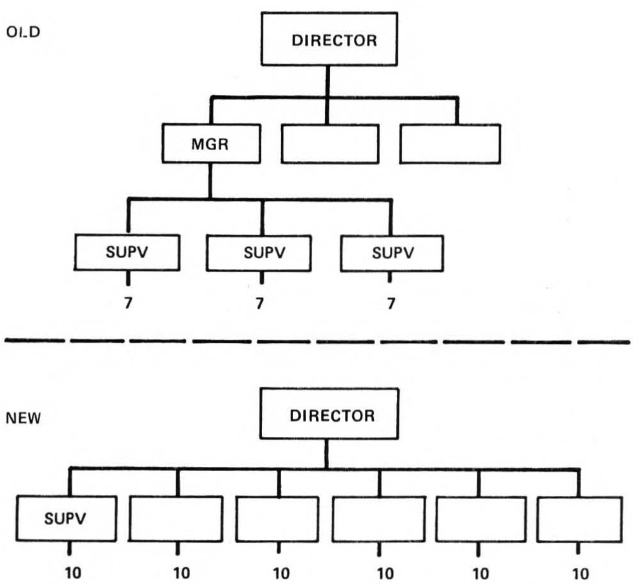
Finally, as mentioned earlier, the United States and Western Europe lost their virtual monopoly on technical capability and the infrastructure needed to support large plants. Developing countries could obtain and operate comparable facilities close to the source of supply. These countries could then price downstream products to support their internal social programs, undercutting our industries, which depended upon scale for their economics. Unfortunately for us, the rules of economics as applied in the United States are not necessarily those of a nation that owns raw materials and abundant unemployed labor but must fuel any real growth with foreign exchange.

The response by industries in the industrialized nations must be to emphasize flexibility, quality, and service rather than scale. The need for technical talent still exists, perhaps more so than in the past, but the emphasis is different. Educational programs should be adapted to produce graduates prepared to function in this new environment.

Organizational Effectiveness

As stated earlier, Du Pont has been hiring fewer engineers lately. Why is that? The need to become more competitive, felt by all American industry and especially in recent years by the chemical and petroleum industries, has resulted in a marked change in organizational structure and attitude. These changes are much more fundamental and significant than indicated by the mere change in numbers; the kind of work and the degree of training and expertise needed are profoundly affected.

In Du Pont, we talk about "organizational effectiveness." In practice, this means doing more with fewer people, cutting out whole layers of supervision, depending more upon nontechnically trained people, and reducing services and administrative support. Figure 3 shows the change in a hypothetical R&D or technical support organization. The total size has been reduced 12%. The number of supervisory or manage-



	OLD	NEW	REDUCTION
SUPERVISORS / MGRS	13	7	46 %
AT BENCH	63	60	5 %
TOTAL	76	67	12 %
RATIO BENCH / MGRS	4.8	8.6	

FIGURE 3. Example of change in a typical technical or R&D organization.

rial slots, however, has been reduced by 46%. The ratio of total people doing technical work to those supervising or managing it in some capacity has increased from about 5 to about 9.

Notice the change in the kind of work that this new structure implies. Only half as many engineers will advance into R&D or technical supervision. The first supervisory opportunity will be at a higher level than before and normally will occur later in one's career. Since there are fewer managerial personnel in the organization, the individuals at the bench will receive less direction. This change in effect upgrades those jobs also, which means that to function effectively those doing technical work will need greater expertise.

Young people ought not to study a field that they do not want to practice and do not enjoy. This advice might sound... ridiculous, but many engineering students view the field as a stepping-stone into management.

Similar changes in manufacturing have resulted in fewer supervisory jobs for engineers, a higher barrier to entry into management, and a longer time spent doing technical work before having an opportunity to try management.

This change in the culture of a company—trying to eliminate all nonessential work and focus on the real business needs—has even greater effects on the staff functions than on line organizations. Most staff jobs are filled by technical people. The result of all this change is more reliance upon the individual and a consequent premium on knowledge and experience. Since training people on the job is much more risky and less affordable now than before, rotational moves are less frequent. When vacancies created by transfer or other reasons are filled, there are no excess people to carry the new person while he learns the new job. Demands upon the replacement to produce quickly are therefore very great.

This development will gradually force a search for more knowledge in the people we hire, manifesting itself in a premium for the master's degree and an increased number of experienced hires. Both trends represent breaks in our tradition. It will also place a greater premium on continuing education of the voluntary, after-hours sort.

Young people ought not to study a field that they do not want to practice and do not enjoy. This advice might sound so apparent as to be ridiculous, but in fact many engineering students view the field as a stepping-stone into management. In the past, it was often possible to move into supervisory jobs within a year or two, and never really learn the practice of engineering at the bench or in the plant. In the future the norm, even for managers, will be to practice engineering for several years before the first supervisory opportunity arises, and so they should be well prepared and motivated to do so. After all, the main criterion for promotion is nearly always to be outstanding at the job one has.

This, then, completes the first part of this paper. Chemical engineers in the future will need to know more and different things than they did in the past and be able to operate more independently at the start of their careers. The typical career path in the chemical industry will be different.

The possibility of employment in other industries and in even greater numbers exists, but only if the graduate fits their needs. Let us turn now to what those needs might be.

INDUSTRY NEEDS

We have considered the ramifications of industry's renewed commitment to providing value to the customer—value as the user sees it, not as the producer might see it. Many commercial blunders and even disasters can be traced back to the sincere but naive belief that the customer would have to be crazy not to want the producer's wonderful product. Producers spent their energy trying to change the customer's perception of value rather than to satisfy his desires.

The academic community has products, too—an array of them. Probably most of all you enjoy producing and marketing your premium products—the fruits of your own research and the PhD's you have personally trained. However, your fixed costs are largely covered by the lower end of your product line—the BS and MS recipients—and you ignore their salability at your peril.

Continuing this analogy, consider what your customers are saying and how their message is being conveyed; only about half the graduates in many chemical engineering schools are getting jobs in the field. If this situation continues, many of your businesses will fold, the smaller and weaker ones first. The problem is more than one of economic cycles. It would not be a good idea to dig in and wait this one out, because there are long-term changes in American industry that will require engineers to have different training in the future than most of them get now. To enjoy a continued expanding demand for your products, you must try two approaches—first, to get your existing customers to buy more, and second, to develop new customers. The approach to either is the same; try to analyze value as they see it, develop a product that provides that value, and then convince potential customers that your product will fill their needs better than any other.

There are potential customers outside the traditional chemical and petroleum industries. Our engineering research organization works with a number of industrial segments involving such diverse technologies as packaging of food products, composites for aerospace and automotive applications, artificial ligaments and diagnostic devices for the health services industry, optical disks, opto-electronic devices and ceramics for the electronics industry, and many others. Opportunities for chemical engineers in those fields are as great as those in the traditional industries hiring chemical engineers. And the general educational requirements are also similar. Therefore, let us consider what industry in general expects from the engineers they hire. We are potentially your customers, but we'll seek value where we find it—from chemical engineers or others.

The first point shown in Table 4 is essential. In the discussions held by the Septenary Committee in Austin, the unanimous opinion held by representatives of the electronics, chemical, and petroleum industries represented on that panel was this: Chemical engineers are uniquely trained to apply fundamentals to complex, unstructured problems of the kind industry faces. When those problems involve molecular change or the separation of chemical species, the present curriculum provides a great deal of additional knowledge that may be brought to bear. We want to enhance those capabilities, not lose them. The assertion that "chemical engineers can do anything" has some evidence to support it, and that reputation is invaluable to those wanting to broaden the employment spectrum of chemical engineers.

TABLE 4
What Industry Expects from ChE Grads

- **Maintain traditional strengths such as ability to deal with complex, real-world problems.**
- **Be able to function productively without extensive additional training.**
- **Be technically oriented.**
- **Have the tools, motivation and ability to continue to learn.**
- **Be able to communicate effectively.**

Special Knowledge

Unfortunately, they cannot do anything well without some specialized knowledge. The traditional curriculum provided that knowledge for the traditional customer. If you wish to broaden your customer base, a way of providing the special tools needed to serve those customers must be devised, which brings up the subject of curriculum.

In a discussion of the undergraduate curriculum, the first question that comes to mind is: "So what? What difference does it make whether a few courses are added or subtracted from the curriculum, or the teaching methods and texts are changed a little? Can't that difference be erased during the first year or so on the job?"

Of course it can—at a price. Many options are available. For example, the new hire can be sent back to school for a master's degree or for supplementary

Continued on page 50.

THE INDUSTRIALIZATION OF A GRADUATE

THE BUSINESS ARENA

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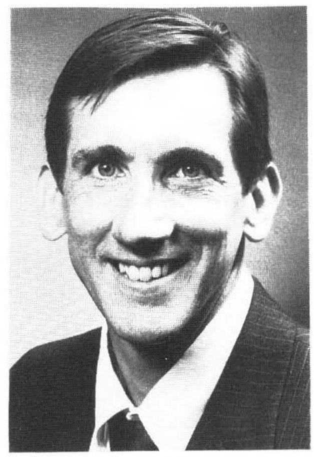
WE HIRE ENGINEERS to effect change, to make things work or work better—but it requires more than technology to be an effective engineer. It requires people skills and a "make-it-happen" mentality. I think that such skills should and can be included in the style of a technical education and that colleges which do so will be recognized by industry as producing faster-starting, more effective graduates.

Throughout my 13-year industrial experience, I found the technical training of engineering graduates to be sufficiently grounded in fundamental principles and concepts to allow the engineer to learn a specific process technology and successfully guide technical decisions. Schools teach technology well. However, humans are involved in the chemical process either as operators or as policy makers and, more often than not, a technical process change simultaneously requires a change in attitudes and perspectives. Technical change, the engineer's job, takes place within a human environment and requires an adeptness with human nature as well as with technology. Unless managers and operators accept it, a technical change will not happen: the engineer will be ineffective. The human awareness required for technical effectiveness is not, but can be, incorporated in the education experience. Because this is a time in which the market demand for new chemical engineers is low, I think that departments which develop industrial savvy in their graduates will have a competitive edge.

For the first twenty years of an individual's life, schools train him/her to be a learner and to work independently. By contrast, an engineer must become a doer and work within a team environment. In growing from student to engineer, an employee must internalize a new understanding of the objective and change his/her approach to the tasks. No business wants an engineer to stop with the statement, "I understand the process now," or "If only they'd accept my idea we could save . . . dollars." Business wants the engineer to "make-it-happen." Performance approaches that make a good student are not necessarily those that make an effective engineer.

By analogy to the socialization process in kindergarten, which prepares children for the teacher/student and peer social structure of school, there is an industrialization process for a new graduate.



R. Russell Rhinehart is an assistant professor of chemical engineering at Texas Tech University. He received his PhD from North Carolina State University after a 13-year industrial career as an engineer and group leader which included development of reaction systems, process control, solvent recovery, and process safety and reliability. His interest in the special aspects of industrial process modeling, optimization, and control techniques led to his pursuit of an academic career.

By analogy to the socialization process in kindergarten, which prepares children for the teacher/student and peer social structure of school, there is an industrialization process for a new graduate. This industrialization process takes about two years, involves several aspects, and has been widely acknowledged [1-5]. With new names for the players, I will draw upon my industrial experiences to provide some examples of the industrialization process.

Although sometimes mathematical analysis is useful, in this instance I missed taking ownership of business need. I appropriated the problem in pursuit of my own personal need which, I think, was to exhibit technical competence. I would like to make two points from my story. The first is to contrast the make-it-happen motive of business in comparison to the "develop skills" motive of the classroom.

In this article I'll describe some of the characteristics of the corporate industrial arena which are both important to business and which constitute major changes from academia. In a subsequent article I'll offer teaching methods which incorporate industrial experience within formal engineering education. Such experiences can accelerate the industrialization process without displacing topics from an already overcrowded curriculum.

MAKE IT HAPPEN

In a competitive business, the fundamental reason for hiring employees is to do a job or to realize a business opportunity, and the profit motive calls for someone who can "make-it-happen." Wanted are active, goal-oriented people who take ownership (internalize responsibility) of the end result and who do whatever task is necessary to make it happen. For example, in business the end result is not an academic task, such as the calculation of an optimum reactor operating temperature; rather, it may be a reduction in operating cost that results after management agrees to a temperature change, after operators are trained in an associated new process procedure, and after a process is smoothly operating at the new temperature without unforeseen hitches (control stability, heater element life, thermal degradation, *etc*). There is an extra-technical perspective required to be effective in industry. Here is a personal example.

I enjoyed engineering math as a student and have the general view that if I can model a process, I can understand it, and I can intelligently optimize it. My confession is important: I enjoy math. In an early project of mine, we were developing a dry-spinning process to extrude a new fiber. Polymer was dissolved in a solvent, the solution was extruded through tiny holes, and as the resulting liquid streams fell, they dried. The continuous filaments of polymer were wound in a criss-cross fashion on a tube to build a wheel-like bobbin. The polymer structure within the filaments was essentially amorphous, and subsequent hot stretching oriented the polymer and strengthened the fiber. The bobbin-wound filament, however, was not totally dry; some residual solvent remained and evaporated from the bobbin surfaces as the yarn waited for subsequent stretching. The bobbin fiber did not dry uniformly. Fiber at the surface dried before the internal bobbin fiber dried; and, since it was wound in a criss-cross manner, the residual solvent level changed every six inches along the length of the continuous filament. The residual solvent acted as a plasticizer and, consequently, the post-stretching process (and resulting fiber properties) changed periodically along the fiber length. Customers don't want such variability.

I saw an application for my training. If I could model the bobbin residual solvent evaporation phenomena, I could determine the length of time one had to wait for the inside-to-surface residual solvent difference to be so low as to not create drawing differences. After several days refreshing my math, diffusion, and evaporation principles and making simplifying assumptions, I was left with one unknown parameter: an effective diffusivity of the solvent through the yarn/air matrix. I then asked the lab to do some effective diffusivity measurements, and about a week later I began to question the validity of the lab-proposed test procedure to simulate the on-bobbin mechanisms. Meanwhile, the fiber draw nonuniformity still existed. Within the business priority list, nothing has happened.

Also meanwhile, two of my co-workers, Ted and "Mr. Clean," saw that we just needed to dry the fiber completely in the first place. So they tried this and that and finally found a way to wind-up with dry yarn. Within about six days all extrusion lines had been modified, the draw uniformity was as desired, and Ted and "Mr. Clean" went out for a beer.

The business goal was to fix the draw uniformity, not to determine the required inventory time through fancy modeling. Although sometimes mathematical analysis is useful, in this instance I missed taking ownership of business need. I appropriated the problem in pursuit of my own personal need which, I think, was to exhibit technical competence.

I would like to make two points from my story. The first is to contrast the make-it-happen motive of business in comparison to the "develop skills" motive of the classroom. The second is to indicate that individual human needs can interfere with a rational view of the objective. Extremely rare is the person who is not driven by personal needs, who does not attempt to exploit situations to get promoted, to exhibit competence, to gain approval, to gain power. . . . To be maximally effective as an engineer (and as a person) one needs to recognize his/her own personal needs and to allow their expression only when they complement the true goal.

Does engineering education train students to make-things-happen? Do students graduate understanding the hidden motives behind human behavior?

CHANGE AND CREDIBILITY

On an average, during my engineering career I had a new supervisor every fifteen months and switched projects every two years. Those changes were in part due to promotions and in part due to transfers in response to business needs. I believe that such change is the rule rather than the exception, and such change has several implications for the employee—one being the engineer's credibility.

The engineer must convince management of his/her proper overall perspective, and because of the constant personnel flux, the engineer must constantly reestablish his credibility.

In order to be effective in convincing management to take a particular action, an engineer's recommendations must be considered credible within a broad interdisciplinary scope. Further, these recommendations must be consistent with the business's traditions, with national values, and with the business's long-term goal and contingency plans. The scope of topics which enters into a business decision is immense, and the required perspective is much greater than the usually myopic, one-technology experience indicated in technical courses.

The engineer must convince management of his/her proper overall perspective, and because of the constant personnel flux, the engineer must constantly reestablish his credibility. Credibility is an image. It is a belief within others that one's work can be accepted. An engineer projects credibility by presenting information from a technical and non-technical perspective which coincides with the listener's priorities and concerns.

Managers are busy people. To make an engineer's work easily accessible to them, the initial sentences of oral and written communication should incorporate the topics which are important to the manager in terms that he understands. The initial statements should also summarize non-technical issues and critique the work. I'll use Neil as an incredible example. He was as technically able and eager to produce as anyone I have seen. His reports were technically complete with assumptions acknowledged and defended and with conclusions analyzed. However, his work came from his own point of view. It did not incorporate the views of production and was not compatible with long-term business goals. It was therefore devoid of some important non-technical business issues, obviously incomplete, and required more analysis before it could add business direction. Technical correctness was his pursuit, and only after pages and pages of development were business consequences addressed (as though they were secondary issues). Neil's exclusively technical approach and the inevitable management frustration are characterized by this anecdote.

Neil and a manager were on a trip and the manager, who was driving, noticed a sign "Highway ends 2 miles." He asked Neil to look at the map and decide whether to turn left or right at the exit.

Neil observed red, blue, and black lines, towns between here and there, and mileage markers on the map. He began to organize his approach to the problem. Then he asked, "What is the most important criteria: to minimize probable time-to-destination, or probable trip-cost?"

"Neil, there's only a mile and a half left. Which is the best way?" Realizing "best" was a fuzzy word the manager asked, "How would you go?"

Wishing to offer a thorough analysis, Neil computed the mileage each way, estimated the toll cost one way, mentally juggled the time delay through a small town, but also considered the advantage of being able to buy cheaper gas in that town. Then there was the possibility of a ticket, which Neil wouldn't get if he were driving, but his manager usually speeds. . . .

"One mile left, Neil," as he eased off the gas.

Finally, Neil gave his report in the familiar technical style of title, abstract, background. . . .

"You asked me which way I'd go," Neil started; and recognizing no quick answer was coming, the manager slowed down a bit more. "The criteria which would guide my choice have been classified, and weighed against them are the possible events which might happen on either route. Additionally, my analysis indicates a third possibility."

"We've only a half mile left, Neil. Left or right?"

"Before I recommend a direction to you, you need to understand the criteria which I used and the assumptions which I made so that you can accept or reject their validity and decide on the appropriateness of the decision. As Dr. X pointed out, these criteria are subjective. For instance, if. . . ."

"NEIL!!" GIVE ME THE MAP!"

Once again, Neil is ineffective in adding direction to his company.

Let's switch Neil for Al in that trip story, and suppose that Al were working for a middle-of-the-road, striped-suit management. The closest Al will come to conforming to that management style is by pedaling his bicycle down the middle of the road with his striped racing tights.

The manager would prefer to hear something like, "Turn left. You can get there either way but the left road promises easier driving. Want more details?"

Does an engineering education teach effective interpersonal communication skills? Does it address professional credibility? Does it foster multidisciplinary thinking? Do we train people to seek and incorporate the concerns of others, or do we train them to work independently?

THE TEAM UNIFORM

Let's switch Neil for Al in that trip story, and suppose that Al were working for a middle-of-the-road, striped-suit management. The closest Al will come to conforming to that management style is by pedaling his bicycle down the middle of the road with his striped racing tights. Al says to his manager, "Turn left . . . easier driving. . . ." The manager may likely glance at Al and scowl to himself, "What's he mean by 'easier' driving? Can I trust someone whose value system and style are so obviously misplaced to guide my decisions? Can Al consider data rationally? After all, look how he wears his hair. Whatever could be guiding his choices?" Then, out loud, he might say "Yes, I want more information. What are the distances either way? Is there an interstate we can take?" Because of the personal image Al presents, and in spite of his competence and business sense, Al causes others to question the propriety of his analysis. Al's professional credibility is questioned, and he is reduced to the position of a technician. How long would you pay an engineer's salary to a technician?

Perhaps it is unfair that personal eccentricities influence our impression of professional competence. But they do. And it is a factor in having power and being effective within a human environment. To make it happen, it is important to "fit in"—to be in harmony with the organization. To be accepted as a leader, one needs to present oneself as part of the team. Although playing well is important, one must also wear the uniform.

Does an engineering education address the irrationalities of human thinking or foster personal adaptability? Does college teach the importance of community or does it reinforce individualism?

NOVICE PROFESSIONALS

Management mobility requires engineers to consciously present a credible professional image, but by contrast, project mobility keeps them in a relatively novice technical state. With moderate technical expertise in the specific technologies of a job, and with pressure to get results, it is commonplace to prematurely accept an apparently successful result.

Margaret, for example, was running a pilot-scale liquid-phase batch reactor with an objective to generate a kinetic expression for a plant reactor design. She postulated a homogeneous phase, first order in each reactant, Arrhenius form of the kinetic expression; and, with experiments which held the initial reactant concentration constant, she measured the initial reaction rate for several temperatures. Paying attention to experimental design practices recently learned in an in-house statistics course, she chose the temperatures randomly. The Arrhenius plot of the data [ln(rate) *vs* $(T)^{-1}$] was a straight line, as beautiful as any encountered in a kinetics and reactor design class, and just had to reflect her proper grasp of the technology. From the plot she got the activation energy and the pre-exponential and proudly reported the results. Her boss, a mechanical engineer, viewed the graphs, listened to her story, and was impressed with her experimental facility. Subsequent trials at a different concentration curiously gave a new slope to another beautiful Arrhenius plot. Thinking it due to uncontrolled experimental conditions, she responsibly revised her kinetic expression—by reporting average values. In her novice state, she did not recognize the possibility that surface phenomena could explain the slope differences and that her data neither confirmed nor rejected the first order assumption. Inexperience accepted a superficially "good" analysis. A year later the startup crew would wrestle for months before the reactor would be operable.

Does engineering education train people to critique their own work, or to view the fallibility of their "knowledge"? What are engineers likely to think of their own ability when they receive good grades in school?

LOCAL TECHNICAL FOLKLORE

With a primary business style of make-it-happen and move-on-to-the-next-project (the Edison approach), there is often little effort at confirming why something worked and why it didn't. Often a technical explanation is postulated tentatively, given as a possible cause, accepted as logical, and, as time proceeds, such hearsay becomes generally established in the local information data base. A tentative position is strengthened as the postulate is subsequently referenced. Technical folklore is indistinguishable from valid technology which also resides in the oral tradition of the operators and long-term plant professionals. It can misguide the work of an engineer and can be a formidable institutional mind-set to change.

As an example, years ago a polymer solution concentration limit of 20% was "established" as the maximum that would still permit extrusion stability of a fiber manufacturing plant. However, increases in concentration promised a significant operating cost reduction. Jim was one of several engineers who interpreted R&D trials to mean that the improved spinerette design and solution purity of the day would allow a concentration increase up to 30%. He knew that temperature adjustments would be necessary to maintain viscosity at the higher concentration. The risks of a plant-wide concentration change were high. Realizing that the factors which affect fiber dyeability are not well quantified, the marketing department saw the possibility of monetary claims if a change in fiber performance on some customer's obscure textile process occurred. The production department feared the havoc that an unstable plant could create. After vice-presidential discussions, it was decided to increase the concentration in 0.1% increments each week over a two-year period. To guide the temperature compensation, Jim would monitor extrusion stability and dye properties. As it happened though, after several months Jim was moved, his projects were distributed among others, and an extrusion upset occurred. Now, a ruptured filter or a crosslink event in polymerization is a normal occurrence which temporarily causes such an upset, but the cause was never identified by those left "in charge." The "too high" concentration was blamed, the plant returned to 20%, and that bit of self-proclaiming folklore was reinforced. Many people within the company now accept the 20% maximum as a given.

Does engineering education train students to unquestionably accept that which they are taught? Could it encourage students to evoke critical thinking?

WHAT WENT WRONG

When quality or productivity is upset, the plant and staff personnel mobilize to determine the cause(s) and to take corrective action. Often the cause is not obvious and, in fact, may be the interaction of several effects. Sometimes a crisis is not even real. I'm reminded of the time a flowmeter calibration error made it appear that we were leaking 200,000 lb/month of solvent. Such a mobilization you never saw when that hit the monthly production reports!

Even in research and development, where we want things to change, I was faced with "Why didn't that work?" more often than "How do I design this?" An efficient engineer can systematically rule out inconsistent hypotheses and find and fix the reason for unexpected behavior.

Does engineering education prepare graduates for systematic diagnostic thinking?

CLOSING

Initially, I stated that colleges do a good job in teaching technology. It must be obvious though, that I also think graduates are ill-prepared for some of the non-technical aspects of an engineering profession. We could easily do a better job in training students to be professionals; and, in a subsequent article, I will suggest some approaches in classroom lecture and homework style, roles of the laboratory, directions for humanity electives, and activities for student professional societies. I find the approaches fun as well as effective.

EDITOR'S NOTE: The second part of Professor Rhinehart's lecture, "Methods for Engineering Education," will appear in the next issue of CEE.

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ChE classroom

SIMPLIFYING CHEMICAL REACTOR DESIGN BY USING MOLAR QUANTITIES INSTEAD OF FRACTIONAL CONVERSION*

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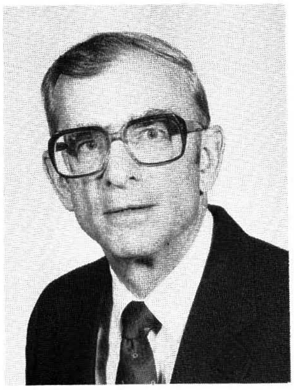
Most chemical reactors are nonisothermal, involve multiple reactions, have mole changes due to reaction, or have reactions with complicated rate expressions. In teaching reactor analysis, it is important that the techniques we present can be applied to these realistic situations; current approaches violate this principle.

In the textbooks on chemical reaction engineering, authors use a variety of dependent variables in reactor mass balances (see Tables 1, 2). The tables show that fractional conversion is employed by a significant majority of authors. We argue here that using fractional conversion in these mass balances is extremely awkward and can lead to serious confusion. Molar quantities as dependent variables in reactor-analysis equations make instruction much easier and chemical reactor design more straightforward. We show this by comparing the use of molar quantities with using fractional conversion for different situations. We also discuss the advantages of using differential versions of reactor mass balances rather than the integrated forms.



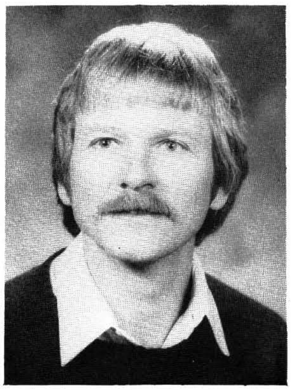


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TABLE 1
Chemical Reaction Engineering Texts Using Fractional Conversion as the Dependent Variable

Butt, 1980	Chen, 1983
Cooper, Jeffreys, 1971	Denbigh, Turner, 1981
Fogler, 1974; 1986	Froment, Bischoff, 1979
Hill, 1977	Holland, Anthony, 1979
Levenspiel, 1962, 1972	Levenspiel, 1979
Peters, Timmerhaus, 1980	Rase, 1977
Smith, 1956, 1972, 1980	Tarhan, 1983

GAS-PHASE SYSTEMS

We begin with the steady-state, gas-phase, plug-flow reactor; extension of the principles to other situations is direct. Consider a gaseous reaction, A → products. The reaction rate r_A is a function of the component concentrations; carrying out a molar balance on substance A over a differential control volume results in

$$\frac{dF_A}{dV} = r_A = f(C_A, C_B, \ldots, C_i, \ldots) \tag{1}$$

in which F_A is the molar flow rate of substance A at a point in the tube, and the C_i's are concentrations at

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The tables show that fractional conversion is employed by a significant majority of authors. We argue here that using fractional conversion in these mass balances is extremely awkward and can lead to serious confusion. Molar quantities as dependent variables in reactor-analysis equations make instruction much easier and chemical reactor design more straightforward.

this point. To solve this equation, both F_A and r_A (and therefore the C_i's) must be expressed in terms of a common dependent variable. Tables 1 and 2 show that the most common dependent variable is fractional conversion. This is the fraction of a substance's entering molar flow rate which has been converted. For a substance A,

$$F_A = F_{A0}(1 - X_A) \qquad \text{or} \qquad X_A = 1 - \left(\frac{F_A}{F_{A0}}\right) \tag{2}$$

Substituting Eq. (2) into Eq. (1) yields

$$F_{A0}\left(\frac{dX_A}{dV}\right) = - f(C_A, C_B, \ldots, C_i, \ldots) \tag{3}$$

To solve Eq. (3), the C_i's must be expressed in terms of the fractional conversion. It will be shown that using fractional conversion in this way frequently leads to extremely awkward formulations of Eq. (1). In other situations, fractional conversion cannot be used at all as a dependent variable in reactor mass balances.

The molar flow rate of the principal component, F_A in Eq. (1), also can be used as the dependent variable. In Eq. (1), the concentrations can be expressed in terms of the molar flow rates and the ideal gas law, *i.e.*,

$$C_i = y_i\left(\frac{P}{RT}\right) = \left(\frac{F_i}{F_T}\right)\left(\frac{P}{RT}\right) \tag{4}$$

and the various F_i's can be related to the dependent variable, F_A, by reaction stoichiometry. This approach offers a simple means for solving Eq. (1).

TABLE 2
Chemical Reaction Engineering Texts Using Dependent Variables Other Than Fractional Conversion

Text	Variable Used
Aris, 1969	extent of reaction, $\epsilon = (F_i - F_{i0})/\alpha_i$
Carberry, 1976	*
Denbigh, 1966; Denbigh, Turner, 1971, 1981	moles product/unit mass
Hougen, Watson, 1947	moles converted/unit mass feed
Hill, 1977**	extent of reaction
Kramer, Westerterp, 1963	mass fraction formed or converted
Petersen, 1965	moles/amt. mass numerically equal to MW of feed
Walas, 1959	moles converted/unit mass feed

*A single dependent variable is not used. A variable is chosen appropriate to the situation being considered.

**Fractional conversion is used in reactor equations (cf. Table 1), but extent of reaction is used in other contexts.

DIFFERENTIAL OR INTEGRAL FORMS OF EQUATIONS?

For most realistic cases, reactor-analysis equations cannot be solved to give analytic closed-form solutions, and numerical techniques must be used. A method such as a Runge-Kutta technique can be used to solve the differential equation or equations directly. In many cases, an alternative attack is possible; the variables can be separated and the integrals evaluated using Simpson's rule or some other scheme.

We prefer the first approach, because separation of variables merely adds an unnecessary step which gives no advantage in solution technique. Moreover, direct solution of the differential equations yields the flow rates, concentrations, temperature, and pressure as functions of location or time in the reactor. This enables the analyst to establish the location or point in time of hot spots, critical concentrations, or dangerous pressures. This is not possible when the separated variables are integrated numerically; to obtain an equivalent result, separate integrations would have to be carried out for each location or time desired.

Most important, though, the approach involving direct solution of the differential equations is better because it can be extended to situations where the variables are not separable, such as nonisothermal reactors with heat exchange, many multiple-reaction systems, and most unsteady-state flow systems. For these reasons, we consider only the differential equations in our comparisons.

CONSTANT-DENSITY SYSTEMS

Constant mass-density reactor systems make a significant class that merits consideration. For example, most liquid-phase systems do not change density much during a chemical reaction. Thus the volumetric flow rate q in liquid-flow reactors is usually not altered significantly, and the molar concentration C_A can be set equal to F_A/q. For this reason, either concentrations or molar flow rates are useful variables in a flow reactor with a constant-density process. However, for an unsteady-state flow system, the numbers of moles of substances in the reactor are the only acceptable dependent variables. This is shown below in the second example.

EXAMPLES

Case 1: Isothermal multiple-reaction system

Reactor system: A gas-phase, steady-state, plug-flow reactor.

Reactions: $A + 2B \xrightarrow{k_1} C \xrightarrow{k_2} D + E$

$\downarrow k_3$

$F + \frac{1}{2}G$

Rate laws:

$$r_A = -k_1 C_A^{\alpha} C_B^{\beta} - k_3 C_A^{\gamma}$$

$$r_B = -2k_1 C_A^{\alpha} C_B^{\beta}$$

$$r_C = k_1 C_A^{\alpha} C_B^{\beta} - k_2 C_C^{\delta}$$

$$r_D = r_E = k_2 C_C^{\delta}; \quad r_F = 2r_G = k_3 C_A^{\gamma}$$

Reactor design equations using molar flow rates:

$$\frac{dF_A}{dV} = -k_1\left[\left(\frac{1}{F_{A0}+F_B+F_E+F_G+F_I}\right)\left(\frac{P}{RT}\right)\right]^{\alpha+\beta}(F_A)^{\alpha}(F_B)^{\beta} - k_3\left[\left(\frac{1}{F_{A0}+F_B+F_E+F_G+F_I}\right)\left(\frac{P}{RT}\right)\right]^{\gamma}(F_A)^{\gamma} \tag{5}$$

$$\frac{dF_B}{dV} = -2k_1\left[\left(\frac{1}{F_{A0}+F_B+F_E+F_G+F_I}\right)\left(\frac{P}{RT}\right)\right]^{\alpha+\beta}(F_A)^{\alpha}(F_B)^{\beta} \tag{6}$$

$$\frac{dF_C}{dV} = k_1\left[\left(\frac{1}{F_{A0}+F_B+F_E+F_G+F_I}\right)\left(\frac{P}{RT}\right)\right]^{\alpha+\beta}(F_A)^{\alpha}(F_B)^{\beta} - k_2\left[\left(\frac{1}{F_{A0}+F_B+F_E+F_G+F_I}\right)\left(\frac{P}{RT}\right)\right]^{\delta}(F_C)^{\delta} \tag{7}$$

$$\frac{dF_D}{dV} = \frac{dF_E}{dV} = k_2\left[\left(\frac{1}{F_{A0}+F_B+F_E+F_G+F_I}\right)\left(\frac{P}{RT}\right)\right]^{\delta}(F_C)^{\delta} \tag{8}$$

$$\frac{dF_F}{dV} = 2\left(\frac{dF_G}{dV}\right) = k_3\left[\left(\frac{1}{F_{A0}+F_B+F_E+F_G+F_I}\right)\left(\frac{P}{RT}\right)\right]^{\gamma}(F_A)^{\gamma} \tag{9}$$

Reactor design equations using fractional conversions:

$$\frac{dX_A}{dV} = k_1 F_{A0}^{\alpha+\beta-1}\left[\left(\frac{1}{F_{A0}[1-X_A+(F_{B0}/F_{A0})-X_{AC}+1.5X_{AF}]+F_I}\right)\left(\frac{P}{RT}\right)\right]^{\alpha+\beta} \cdot \left[(1-X_A)^{\alpha}\left(\frac{F_{B0}}{F_{A0}}-2X_{AC}\right)^{\beta}\right] + k_3 F_{A0}^{\gamma-1}\left[\left(\frac{1}{F_{A0}[1-X_A+(F_{B0}/F_{A0})-X_{AC}+1.5X_{AF}]+F_I}\right)\left(\frac{P}{RT}\right)(1-X_A)\right]^{\gamma} \tag{10}$$

$$\frac{dX_{AC}}{dV} = k_1 F_{A0}^{\alpha+\beta-1}\left[\left(\frac{1}{F_{A0}[1-X_A+(F_{B0}/F_{A0})-X_{AC}+1.5X_{AF}]+F_I}\right)\left(\frac{P}{RT}\right)\right]^{\alpha+\beta} \cdot \left[\left(1-X_A\right)^{\alpha}\left(\frac{F_{B0}}{F_{A0}}-2X_{AC}\right)^{\beta}\right] - k_2 F_{A0}^{\gamma-1}\left[\left(\frac{1}{F_{A0}[1-X_A+(F_{B0}/F_{A0})-X_{AC}+1.5X_{AF}]+F_I}\right)\left(\frac{P}{RT}\right)(X_{AC})\right]^{\gamma} \tag{11}$$

$$\frac{dX_{AD}}{dV} = k_2 F_{A0}^{\delta-1}\left[\left(\frac{1}{F_{A0}[1-X_A+(F_{B0}/F_{A0})-X_{AC}+1.5X_{AF}]+F_I}\right)\left(\frac{P}{RT}\right)(X_{AC})\right]^{\delta} \tag{12}$$

$$\frac{dX_{AF}}{dV} = k_3 F_{A0}^{\gamma-1}\left[\left(\frac{1}{F_{A0}[1-X_A+(F_{B0}/F_{A0})-X_{AC}+1.5X_{AF}]+F_I}\right)\left(\frac{P}{RT}\right)(1-X_A)\right]^{\gamma} \tag{13}$$

Comments: Using the fractional conversion in multiple-reaction systems requires the definition and use of several subsidiary fractional conversions. In this example, X_{AC} is the fraction of A converted only to C, not to D, E, F, or G; X_{AD} is the fraction of A converted only to D; X_{AF} is the fraction of A converted only to F, and $X_A = X_{AC} + X_{AD} + X_{AF}$. Not only are the mass balances much simpler when molar flow rates are used, but they do not require the tortured mental convolutions necessary for implementation of the subsidiary fractional conversions. The denominators in the mass balances are especially difficult for students to create correctly. As shown above, the molar flow rates are straightforward to define and use, even in complicated, multiple-reaction systems.

Of the differential equations presented for each approach, only three are necessary, since only three independent reactions occur. Stoichiometric equivalences can determine the other flow rates, *e.g.*, $F_F = F_{A0} - (F_A + F_C + F_D)$.

Case 2: Isothermal stirred tank with outflow

Reactor system: A tank reactor with a steady outflow starting at $t = 0$. Initial charge contains reactant A and inerts; the outflow volumetric flow rate is q_f. This might describe a leaking nuclear waste site.

Reaction: $A \xrightarrow{k} B$

Rate law: $r_A = -kC_A$

Reactor design equations using molar quantities:

$$\frac{dN_A}{dt} = -kN_A - q_f\left(\frac{N_A}{V}\right) \tag{14}$$

$$V = V_0 - q_f t \tag{15}$$

Reactor design equation using fractional conversion: *None possible.*

Comments: Using molar quantities, the mass balance can be integrated analytically; the solution is

$$N_A = N_{A0}e^{-kt}[1 - (q_f t/V_0)] \tag{16}$$

This is one of the simplest unsteady-state reactor systems, yet it appears impossible to express the mass balance in terms of fractional conversion without also including at least one molar quantity as a variable. Because A reacts, leaves, or remains in the reactor,

$$N_A(t) = N_{A0}[1 - X_A(t)] - q_f \int_0^t [N_A(\beta)/V(\beta)]d\beta \tag{17}$$

and N_A must also be included as a variable. Hill [11, p. 301] has noted this difficulty. In contrast, the substance A in a batch reactor is restricted to either reacting or remaining in the reactor, and N_A can be expressed as $N_{AO}(1-X_A)$. Similarly, in a steady-state, stirred-tank flow reactor, A either reacts or leaves, and F_A can be expressed as $F_{AO}(1-X_A)$. For unsteady-state systems with an outflow stream, too many possibilities are present, and fractional conversions cannot be used.

Case 3: Reactor with an entering side stream

Reactor system: Steady-state, isothermal, plug-flow reactor with entering side stream F_{A10}. Feed contains A and inerts; the side stream entering the reactor at point V_1 is pure A. This configuration avoids a high initial concentration of A in order to reduce production of undesired product C.

Reactions: $A \xrightarrow{k_1} B$ (desired); $2A \xrightarrow{k_2} C$ (undesired)

Rate laws: $r_A = -k_1C_A - 2k_2C_A^2$

$r_B = k_1C_A$; $r_C = k_2C_A^2$

Reactor design equations using molar flow rates:

$$F_A = F_{A0} - F_B - 2F_C \tag{18}$$

$$\frac{dF_B}{dV} = k_1\left[\left(\frac{1}{F_{AT0} - F_C + F_I}\right)\left(\frac{P}{RT}\right)\right]F_A \tag{19}$$

$$\frac{dF_C}{dV} = k_2\left[\left(\frac{1}{F_{AT0} - F_C + F_I}\right)\left(\frac{P}{RT}\right)\right]^2 F_A^2 \tag{20}$$

B.C.: At $V = 0$: $F_A = F_{A0}$; $F_{AT0} = F_{A0}$

At $V = V_1$: $F_{A1+} = F_{A1-} + F_{A10}$; $F_{AT0} = F_{A0} + F_{A10}$ (21)

Reactor design equations using fractional conversions:

$$X_A = X_{AB} + X_{AC} \tag{22}$$

$$\frac{dX_{AB}}{dV} = k_1\left(\frac{1}{F_{AT0}(1 - \frac{1}{2}X_{AC}) + F_I}\right)\left(\frac{P}{RT}\right)(1 - X_A) \tag{23}$$

$$\frac{dX_{AC}}{dV} = k_2\left(\frac{1}{F_{AT0}(1 - \frac{1}{2}X_{AC}) + F_I}\right)^2\left(\frac{P}{RT}\right)^2 F_{AT0}(1 - X_A)^2 \tag{24}$$

B.C.:

At $V = 0$: $F_{AT0} = F_{A0}$; $X_{AB} = 0$; $X_{AC} = 0$

At $V = V$: $F_{AT0} = F_{A0} + F_{A10}$; $X_{AB1+} = (F_{A0}X_{AB1-})/(F_{A0} + F_{A10})$;

$X_{AC1+} = (F_{A0}X_{AC1-})/(F_{A0} + F_{A10})$ (25)

Comments: Here, use of fractional conversions not only makes the mass balances more involved, but severely complicates the boundary conditions.

Case 4: Energy balance for reactor with heat transfer.

Reactor system: Nonisothermal, gas-phase, plug-flow reactor with heat transfer (catalytic oxidation of o-xylene to produce phthalic anhydride).

Reactions:

$A + 3B \xrightarrow{k_1} C + 3D$

$C + 7.5B \xrightarrow{k_2} 2D + 8E$

$A + 10.5B \xrightarrow{k_3} 5D + 8E$

(A is o-xylene,
B is oxygen,
C is phthalic anhydride,
D is water,
E is carbon dioxide)

Rate laws [11]:

$r_A = -k_1C_A - k_3C_A$ $[k_i = A_i \exp(-E_i/RT)]$

$r_B = -3k_1C_A - 7.5k_2C_C - 10.5k_3C_A$

$r_C = k_1C_A - k_2C_C$

$r_D = 3k_1C_A + 2k_2C_C - 5k_3C_A$

$r_E = 8k_2C_C + 8k_3C_A$

Energy balance equation using molar flow rates:

Another benefit to using the differential equations occurs because students tend to memorize the integrated forms for particular cases. They then use the integrated forms even when the variables are not separable. This happens much less frequently when the differential-equation approach is taught.

$$\frac{dT}{dV} = \left(\frac{1}{F_A C_{PA} + F_B C_{PB} + F_C C_{PC} + F_D C_{PD} + F_E C_{PE} + F_I C_{PI}}\right) \cdot \left[\left(\frac{1}{F_A + F_B + F_C + F_D + F_E + F_I}\right)\left(\frac{P}{RT}\right)\right] \cdot \left(\begin{array}{l} A\, e^{-E_1/RT}(F_A)(-\Delta H_{r1}) + A_2 e^{-E_2/RT}(F_C)(-\Delta H_{r2}) \\ \quad + A_3 e^{-E_3/RT}(F_A)(-\Delta H_{r3}) - (4U/D)(T-T_{ex}) \end{array}\right) \tag{26}$$

Energy balance equation using fractional conversions:

$$\frac{dT}{dV} = \left(\frac{1}{\begin{array}{l} F_{AO}\{(1-X_A)C_{PA} + [(F_{BO}/F_{AO}) - (3X_{AC} + 10.5X_{AE})]C_{PB} \\ \quad + X_{AC}C_{PC} + (3X_{AC} + 5X_{AE})C_{PD} + 8X_{AE}C_{PE}\} + F_I C_{PI} \end{array}}\right) \cdot \left[\left(\frac{1}{F_{AO}(1-X_A + X_{AC} + 2.5X_{AE}) + F_{BO} + F_I}\right)\left(\frac{P}{RT}\right)\right] \cdot \left(\begin{array}{l} F_{AO}[A_1 e^{-E_1/RT}(1-X_A)(-\Delta H_{r1}) + A_2 e^{-E_2/RT}(X_{AC})(-\Delta H_{r2}) \\ \quad + A_3 e^{-E_3/RT}(1-X_A)(-\Delta H_{r3})] - (4U/D)(T-T_{ex}) \end{array}\right) \tag{27}$$

Comments: Only the energy balance is presented here; the superiority of the molar quantity approach in multiple-reaction mass balances was illustrated in Case 1. In energy balances as in mass balances, the molar-quantity approach is invariably more straightforward for all but the simplest systems. If fractional conversions are used, the denominators, especially in energy balances, become extremely complex and are difficult to derive and explain.

ADDITIONAL ADVANTAGES TO MOLAR QUANTITIES

When fractional conversion is used as a dependent variable in mass and energy balances, additional parameters are sometimes introduced to simplify the forms of the equations. For example, parameters have been defined for molar ratios of feeds and for volume change upon reaction [15, 11, 8]. Introduction of these parameters is not necessary when molar quantities are used; rather, retention of the molar quantities in the numerical algorithm makes these parameters unnecessary.

Earlier, we presented several advantages of using differential equations instead of using the integrated forms. Another benefit to using the differential equations occurs because students tend to memorize the integrated forms for particular cases. They then use the integrated forms even when the variables are not separable. This happens much less frequently when the differential-equation approach is taught.

CONCLUDING REMARKS

Teaching of undergraduate reactor design can be improved by using molar quantities as variables in the differential equations for the mass and energy balances. This approach has several advantages over the more common approach of using fractional conversion in the integrated versions of the balances:

1) Most industrial reactor systems contain multiple reactions, nonisothermal reactors, pressure drop, complicated rate expressions, and reactions with mole changes. The equations must be solved numerically, and this approach can be directly applied to these systems. If students are taught other methods, they must still learn this approach to do practical calculations since fractional conversions are unsuitable as a design variable for complicated systems.

2) For semibatch reactors, unsteady-state CSTR's, and systems with side streams, fractional conversion cannot be defined easily. The use of molar quantities in these systems is straightforward.

3) Separate parameters are not needed to handle mole changes in gas-phase reactions.

4) By solving the differential equations instead of separating the variables and integrating the balances, the flow rates and temperatures are obtained at points along the reactor length (or molar amounts are obtained as functions of time in a batch reactor) instead of only at the end point.

5) Molar quantities are physically more interpretable variables in many cases. For example, the molar flow rate does not change when the temperature or pressure changes, or when inerts are added. On the other hand, the concentration changes when temperature, pressure, or amount of inerts is changed, and the parameter accounting for volume variation changes when inerts are added. *The molar flow rate will change only due to chemical reaction when no material is removed or added before the reactor exit.*

ACKNOWLEDGMENTS

The seminal contribution of Dr. Jack K. Nyquist of E. I. DuPont de Nemours & Co. is acknowleged. While a graduate student at the University of Colorado in the 1960's, he convinced one of the authors (LFB) of the superiority of the molar-quantities approach. The use of a form of the molar-quantities approach in the book by Franks [9] also contributed to the authors' formulation of ideas in this area. Discussions with other Boulder faculty members, especially with Professor David E. Clough, have been very helpful.

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NOMENCLATURE

Roman

A	pre-exponential factor in Arrhenius expression for reaction-rate "constant," various units
C	concentration, mol/m^3
C_P	molar heat capacity, J/(mol)(K)
D	diameter of tubular reactor, m
E	activation energy of reaction, J/mol
F	molar flow rate, mol/s
ΔH_r	change in enthalpy upon reaction, J/mol
k	reaction-rate "constant," various units
N	number of moles in reactor, mol
P	total pressure in reactor, Pa
q	volumetric flow rate, m^3/s
R	universal gas constant, (Pa)(m^3)/(mol)(K) or J/(mol)(K)
r	reaction rate, mol created/(m^3)(s)
T	temperature, K; without subscript, the temperature of the reacting fluid, K
t	time, s
U	overall heat transfer coefficient between reacting fluid and external heating or cooling medium, J/(s)(m^2)(K)
V	reactor volume or volume of reacting mixture, m^3
X	fractional conversion, dimensionless
y	mole fraction, dimensionless

Greek

α	stoichiometric coefficient, dimensionless
β	dummy variable in Eq. (17), s
ϵ	extent of reaction, mol/s

Subscripts

A, B, C, D, E, F, G	of substances A, B, C, D, E, F, or G
ex	of external heating or cooling medium
f	final value or relating to the effluent stream
I	of inert components
i	of the i'th component or of the input stream
O	at the entrance to the reactor or at time zero
T	total amount
1	referring to point 1 in reactor
1,2,3	referring to Reaction 1, 2, or 3

Superscripts

Superscripts indicate order of reaction with respect to the superscripted term. □

CHEMICAL REACTION EXPERIMENT FOR THE UNDERGRADUATE LABORATORY

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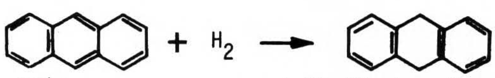
Tuskegee's chemical engineering Department was founded in 1977 and was accredited by the EAC/ABET in 1983. There are approximately eighty students presently enrolled. Three chemical engineering laboratory classes are taught; one for junior students and two for senior students. The first laboratory class consists mainly of fluid mechanics and heat transfer experiments. The second laboratory consists mainly of mass transfer, thermodynamics and chemical reaction experiments, as shown in Table 1. Approximately twelve of the experiments are done in any one semester with the choice being made by the instructor. The third chemical engineering laboratory consists of process control experiments. The laboratory classes are offered twice a year with an average class size of ten students, usually divided into three groups. Each student must analyze the data, make the necessary calculations and submit a written report conforming to acceptable standards.

CHEMICAL REACTION EXPERIMENT

For Experiment 16, anthracene is hydrogenated with molecular hydrogen in the absence of catalyst in a batch-type microreactor to identify the reaction order, the reaction rate constant, the frequency factor and the activation energy for the anthracene-hydrogen reaction system shown in Eq. 1.



anthracene 9,10-dihydroanthracene (1)

EQUIPMENT DESCRIPTION

The 316 stainless steel microreactor assembly consists of a 1/2 inch tee, an 11-inch piece of high pressure 3/8″ O.D. tubing and a shut-off valve. The tee is the

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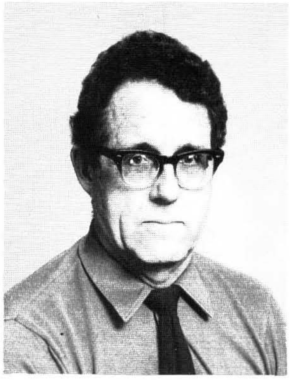

N. Vahdat is Coordinator of the Chemical Engineering Department at Tuskegee University. He received his BS from Abadan Institute of Technology, Iran, his MS from the University of California, and his PhD from the University of Manchester, England. His research interests include thermodynamics of solutions and transport properties of polymer systems. **(C)**

W. R. Ayers is a visiting faculty member at Tuskegee University. He received his BChE (1952) from Clarkson University. He was a field engineer with DuPont's engineering department from 1951 to 1959, a process engineer with Thiokol Corporation from 1959 to 1960 and a process engineer/senior research engineer with DuPont's Pigments Department (now C&P Department) from 1960 to 1981 when he retired. His research interests are primarily related to DuPont's chloride process for the manufacture of titanium dioxide pigment. **(R)**

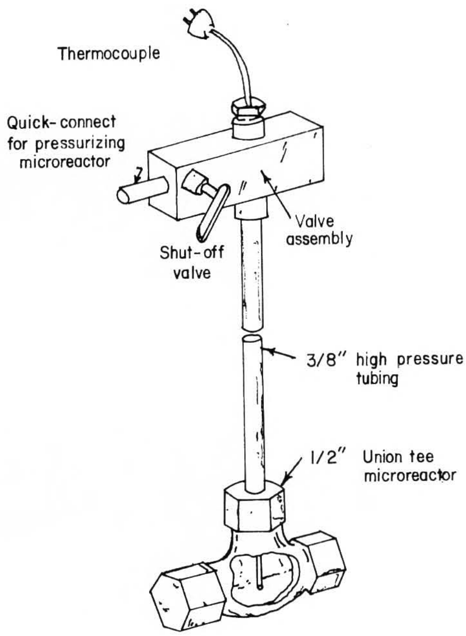

FIGURE 1. Microreactor Assembly

actual microreactor and is connected to the shut-off valve by the 3/8" tubing (see Figure 1). A thermocouple extends through the tubing and into the microreactor, allowing temperature monitoring of the reactants throughout the experiment. A quick-connect is attached to the shut-off valve in order to introduce hydrogen into the microreactor assembly during charging and to release excess hydrogen from the

TABLE 1
List of Experiments for the ChE LAB II

EXP. NO.	DESCRIPTION
1	Continuous Distillation with Total Reflux
2	Continuous Distillation with Feed at Bubble Point
3	Batch Distillation in a Packed Column
4	Fluid Flow Through a Packed Column
5	Flow Through a Fluidized Bed
6	Filtration
7	Gas Chromatograph
8	Evaporation
9	Vapor-Liquid Equilibria
10	Liquid-Liquid Equilibria
11	Liquid Extraction
12	Hydrodynamics of a Packed Column
13	Absorption of CO_2 in Water/Analysis of Gas Streams
14	Absorption of CO_2 in Water/Analysis of Liquid Solutions
15	Heats of Solution
16	Reaction Kinetics of the Anthracene-Hydrogen System
17	Spray Drying

Three laboratory classes are taught; one for juniors and two for seniors. The first consists mainly of fluid mechanics and heat transfer experiments. The second consists mainly of mass transfer, thermodynamics and chemical reaction experiments.

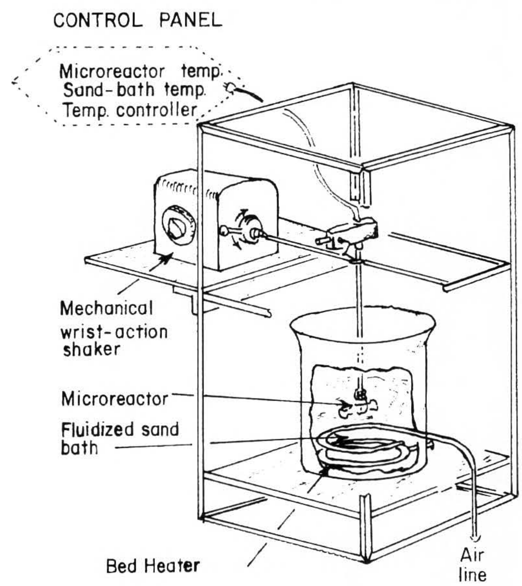

FIGURE 2. Fluidized Sand Bath

microreactor after an experimental run is completed. The total internal volume of the microreactor is roughly 13 cc. The microreactor assembly is submerged and heated in a fluidized sand bath (see Figure 2) and is shaken throughout the experimental run in order to eliminate the mass transfer effects. The sand bath temperature is adjusted using a thermocouple and temperature controller.

EXPERIMENT DETAILS

A series of anthracene hydrogenation experiments is conducted at 375°C, 400°C, and 425°C. The microreactor is charged with 0.1 g anthracene, 2.0 g 1-methylnaphthalene as a physical solvent and 1200 psig hydrogen at room temperature. After being charged with the reactants, the reactor is attached to the shaker mechanism and is submerged in the preheated fluidized sand bath.

Following hydrogenation of anthracene at the desired reaction time and temperature, the reactor is quenched in cold water and the excess hydrogen is released. The liquid products, consisting of anthracene, 9-10 dihydroanthracene and 1-methylnaphthalene, are injected into a gas chromatograph,

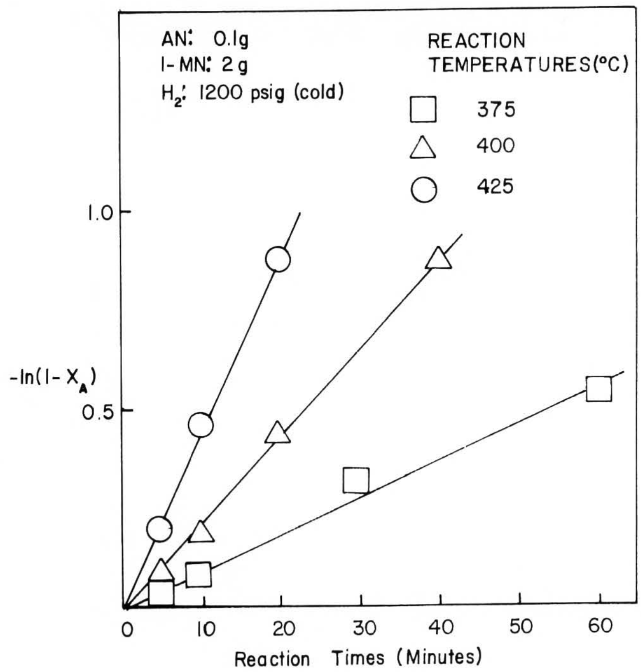

FIGURE 3. Conversions of Anthracene vs. Reaction Times

equipped with a flame-ionization detector, an integrator-plotter and an 8 ft. long, 1/8 inch O.D., SP 2100 packed column, to analyze conversions of anthracene to 9,10-dihydroanthracene.

DATA ANALYSIS

The reaction data, anthracene conversions *vs* reaction times, are plotted on semi-logarithmic paper to identify the reaction order for the anthracene-hydrogen system. A typical plot is shown in Figure 3 and produces a straight line through the origin, indicating that the anthracene-hydrogen reaction system is first order. Reaction rate constants are calculated by applying conversion *vs.* reaction time data to the first-order reaction equation, as shown in Eq. 2.

$$-\ell n\ (1 - X_A) = kt \tag{2}$$

where X_A = fractional conversion of anthracene
k = reaction rate constant, min^{-1}
t = reaction time, minutes

The activation energy and the frequency factor for the anthracene-hydrogen reaction system were found to be 2.699 x 10^7 cal/gmole and 1.215 x 10^4 min^{-1}, respectively, by applying reaction rate constant *vs* reaction temperature data to the Arrhenius' Law, as shown in Equation 3 and Figure 4.

$$k = k_o \exp(-\Delta E/RT) \tag{3}$$

where k = reaction rate constant, min^{-1}
k_o = frequency factor, min^{-1}
ΔE = activation energy, cal/gmole
R = ideal gas constant, cal/gmole-K
T = reaction temperature, K

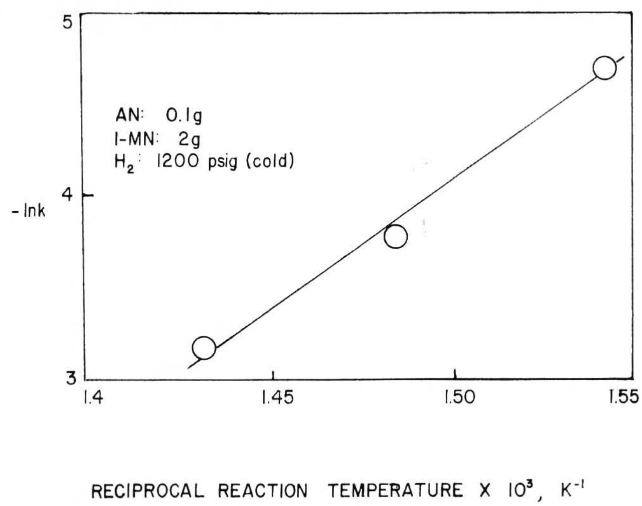

FIGURE 4. Reaction Rate Constants vs. Reaction Temperatures

CONCLUSION

A series of reaction samples is obtained by performing reaction runs at the desired hydrogenation temperatures and times. These samples are analyzed using a gas chromatograph.

This batch-type microreactor has several advantages over other type reactors in carrying out reaction experiments for undergraduate laboratory classes:

- It takes a short time (1 minute) to increase reactor temperatures from an ambient temperature to a desired reaction temperature in comparison with conventional autoclave reactors. Therefore, several experimental runs can be conducted during the 3-hour class.
- It is easy to clean a reactor after finishing a reaction experiment and then to prepare another experimental setup.
- Reactants such as anthracene, 1-methylnaphthalene and hydrogen are needed in small quantities, in comparison with other conventional autoclave reactors.
- There are fewer leakage problems with microreactors during reaction experiments at high temperatures and pressures, in comparison with conventional autoclave reactors which utilize stirring systems. □

REVIEW: Economic Evaluation

Continued from page 5.

of process applications.

The book is broken down into six chapters with the first chapter giving a very simple survey of the principles of economic evaluation with many generalizations. The second chapter is on the subject of capital and is an adequate survey for providing overall information with few details. Chapter Three on production costs and Chapter Four on capacity economics are presented in the same general survey form as Chapter Two, with a very simplified description, a few illustrations, and definition of terms. Probably the most useful chapter in the book is the fifth chapter which deals with year-by-year economics. It is almost completely a word discussion, with no base equations being given for the relationships which are presented in the numerous examples. This chapter gives the general ideas of discounted cash flow, net present value, and year-by-year accounting, but very little useful quantitative information on the various methods is given. There is nothing included on income taxes or modern depreciation based on recent Federal laws.

The final chapter on computer processes is a very simplified presentation based on flow diagrams and block schedules. No examples and no problems are included. The book concludes with a seven-page glossary of terms and a twelve-page index.

The book can serve as a useful over-view for economic evaluation in the chemical process industries, but it would not serve as a teaching text because of the lack of quantitative information. The material it presents is given in easy-to-understand language with very little mathematics background required. It would be of use as an introduction to the subject for someone who needed to get an overall picture of the methods and basis of economic evaluation for industrial processes without getting into technical details. □

PRINCIPLES OF POLYMER SYSTEMS, 2ND EDITION

by Ferdinand Rodriguez; McGraw-Hill Book Company,
New York, 1982; pages xvi, 575, $29.95

Reviewed by
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University of Texas at Austin

The first edition of this book appeared in 1970 as a text for polymer courses primarily in chemical engineering departments, although at that time not many departments taught such courses. The second edition is part of the well-known and respected McGraw-Hill Chemical Engineering Series. This fact may be taken as one indication of the degree to which instruction in polymers has been incorporated into chemical engineering departments since 1970.

The second edition follows the same format as the first and is essentially an updated version of that book. While substantial progress has occurred in the science and technology of polymers during the years between the appearance of the first and second editions, the goal of the book is to present to the beginning student basic principles of the subject which largely remain timeless; however, all of the dated content of the first edition, such as production statistics, has been appropriately made current. The lengths of both editions are approximately the same so about the same amount of material was removed as was added. The main strengths of the new version are more problems at the end of various chapters, plus greatly expanded lists of specific and general references which should help introduce the student to the modern literature.

The first three chapters deal with basic issues of polymer molecular and physical structure to give a framework for understanding properties. The next three chapters are devoted to polymerization reactions and processes and the closely linked issue of the description and measurement of molecular weight and its distribution. The following three chapters deal with rheological behavior ranging from laminar flow of solutions and melts, to viscoelasticity at small deformations and finally ultimate failure properties of polymers under use-type conditions. The next chapter introduces the reader to other types of properties than mechanical ones with a strong, and appropriate, emphasis on electrical behavior. The following chapter deals with types and mechanisms of polymer degradation with equal focus on how these problems can be avoided or solved by the use of various additives. This is a feature unique to this textbook and is one of its really strong points. The reader is then introduced qualitatively to some of the common processing and fabricating techniques. The entire book could be made stronger at this point by more detailed analyses of some of these operations to show how rheological data, introduced earlier, can be used in practice and how molecular weight and its distribution is a powerful way of tailoring polymers for these specific processing methods. In turn, an excellent opportunity could have been provided to show the chemical engineering student how the latter ties to the polymerization mechanism, conditions, and process to give a glimpse of the strong interrelationship between each of these

Continued on page 46.

MICROCOMPUTER-AIDED CONTROL SYSTEMS DESIGN

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THE LOW PRICE and interactive nature of personal microcomputers have led to their widespread use in chemical engineering education in a variety of applications. Several universities now require students to own PC's, and at most others personal computer laboratories are readily available to students. Microcomputer software is rapidly being developed to demonstrate and teach various aspects of chemical engineering [1,2]. Chemical engineering process dynamics and control is a course particularly well suited for microcomputer application.

This paper describes a single input/single output feedback control systems design program for IBM PC and compatible microcomputers. Menu-driven, interactive, and user-friendly, it displays control systems in terms of block diagrams and uses the graphics capability of the computer in presenting results. The scope of exercises that can be given using this program may be inferred from the main menu shown in Figure 1.

The program is limited to those systems which can be described in terms of first order transfer functions

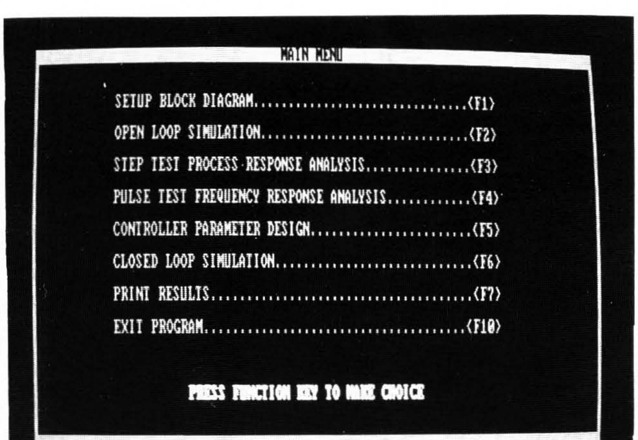
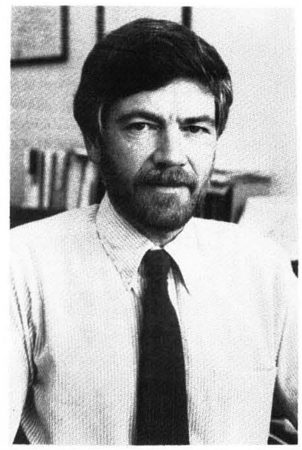


FIGURE 1. Main Menu Screen



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and pure time delays, but the open loop system can have an overall order of up to four. Thus, the control loop to be studied can be rather complex and challenging, but open loop underdamped systems are excluded, as are non self-regulating processes.

A heat exchanger temperature control loop used for a number of examples in the textbook by Smith and Corripio [3] will be used to illustrate the various applications of the program. A schematic depiction and a block diagram for this system (page 177, 179 of Smith and Corripio) are shown in Figure 2. The transfer functions are as follows

$$G_V = 0.016/(3s + 1) \qquad G_F = -3.33/(30s + 1)$$

$$G_S = 50/(30s + 1) \qquad G_T = 1/(30s + 1)$$

$$H = 1/(10s + 1)$$

where G_v is the final control element (valve), and H is the measuring element (sensor-transmitter). G_S is

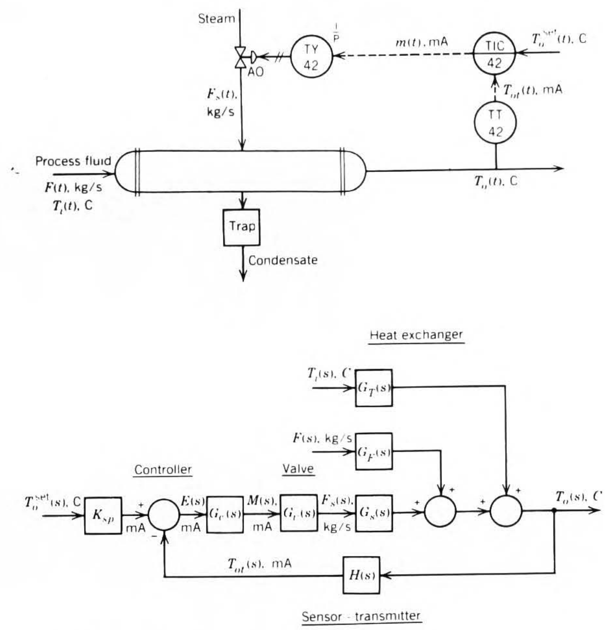

FIGURE 2. Schematic and Block Diagrams for Heat Exchanger Control Loop (Reprinted from* Principles and Practice of Automatic Process Control, *Smith and Corripio; John Wiley, 1985)

the process transfer function for the manipulated input (steam), and G_T and G_F are the process transfer functions for disturbances in the input temperature and flow rate respectively. The controller, G_c, is to be designed by the student.

OPEN LOOP SIMULATION

The loop is first configured as shown in Figure 3. Note that deadtime (transportation delay) is permitted in both Process 2 and the Measuring Element. The open loop system response to either a servo (manipulated input) or load (disturbance) forcing may be computed with either step or pulse input functions. For a disturbance forcing in the example problem, Process 3 would be used to represent either G_T or G_F as appropriate. The "actual response" in Figure 4 shows a step response plot obtained for a manipulated input forcing for the heat exchanger control system. This plot can be easily recorded on a dot-matrix printer, and a printed listing of the system response can be obtained as well.

This paper describes a single input/single output feedback control systems design program for IBM PC and compatible microcomputers. Menu-driven, interactive, and user-friendly, it displays control systems in terms of block diagrams and uses the graphics capability in presenting results.

One simple exercise with the program is to have the student simulate a first order process (*e.g.*, G_s in this system), and then sequentially add additional lags and/or deadtimes to the system. The effect of lags on the system response can thus be seen very graphically.

SYSTEMS IDENTIFICATION

In practice, analytic models for the elements in a control loop are often not available, and experimental testing must be used to identify a model for the process. This may be done either directly from time domain response data, or by tranforming the data into the frequency domain to get a system Bode plot. The control system design package provides for both time domain analysis of step response data ("process reaction curve" modeling) and frequency domain analysis of pulse test data. The program is designed so that

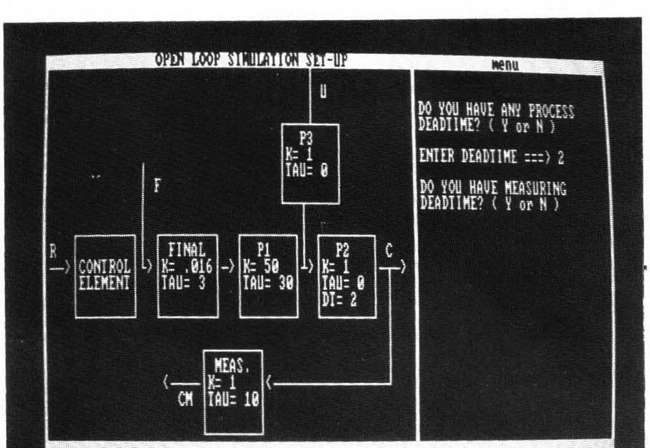

FIGURE 3. Block Diagram Setup Screen

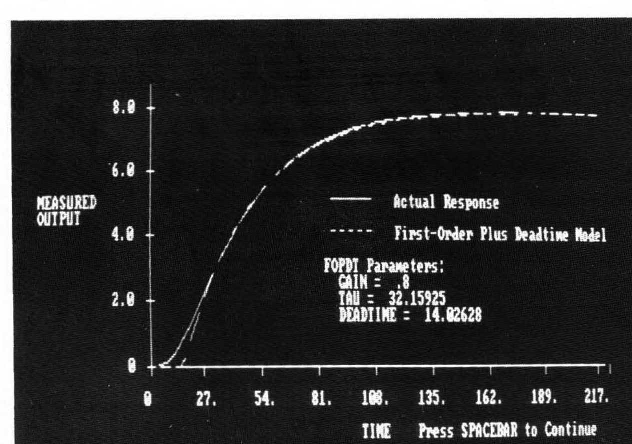

FIGURE 4. Open Loop Response and First-Order Plus Deadtime Model

the data to be analyzed is read from a file on disk. Exercises may thus be given where the data is obtained from an open loop simulation as described above, but the program may also be used to analyze data obtained from a different computer simulation, or from laboratory experiments.

STEP TEST MODELING

The first-order plus deadtime (FOPDT) model is commonly used to fit step response data from overdamped systems [3]. It is easily and reliably fit, and a number of feedback controller tuning formulas are based on it. The FOPDT transfer function is

$$\frac{C(s)}{m(s)} = G(s) = \frac{Ke^{-t_o s}}{\tau s + 1} = \frac{\text{Process output}}{\text{Process input}} \tag{1}$$

where K, τ, and t_o are the gain, time constant, and apparent deadtime to be determined. The time domain solution for a step forcing of magnitude A is

$$c(t) = KA\left[1 - e^{-(t-t_o)/\tau}\right]u(t - t_o) \tag{2}$$

where u is the unit step function. The actual response curve in Figure 4 is a "typical" step response, or "process reaction curve."

The process gain, K, is obviously

$$K = \frac{C_{ss}}{A} \tag{3}$$

where C_{ss} is the final value of the process output. There are numerous methods of determining the values of t_o and τ to fit the model to the curve [3]. In the earliest method developed, a line is drawn tangent to the curve at the point of maximum slope. The deadtime, t_o, is then the time at which the tangent line intersects the abscissa, and the time constant is given by

$$\tau = \frac{A}{S} \tag{4}$$

where S is the slope of the tangent line. Another method fits the model through the actual step response curve at two points. Recommended values [4] are where the response reaches 28.3% and 63.2% of the final value. In Eq. (2), this is at $t_1 = (t_o + \tau/3)$ and $t_2 = (t_o + \tau)$ respectively. Thus,

$$\tau = \frac{3}{2}(t_2 - t_1) \tag{5}$$

$$t_o = t_2 - \tau \tag{6}$$

Other variations on these schemes are discussed in introductory control texts [3,5,6,7,8]. The curve fitting method used in the program is similar to the second method described above. However, it fits the FOPDT model to the process reaction curve in a least squares sense over the range of 20% to 80% response. For accurate, non-noisy data, the results are very close to Eqs. (5) and (6). However, the least squares fit would be less susceptable to error should the data be noisy. The program displays the FOPDT model response on the same screen as the actual response curve for comparison. Figure 4 shows the results for the example system described earlier. Students can be assigned to compare the FOPDT models obtained from the computer curve-fit to those from one or more hand calculated fits.

FREQUENCY DOMAIN MODELING

If frequency response data on a system can be obtained, it is possible to fit a transfer function that is more complex than the FOPDT model discussed above. In addition, well-established controller tuning criteria [9] are available which are based on the open-loop system frequency response data. The most common method of obtaining such data in chemical process applications is by Fourier analysis of pulse-test data. Direct sinusoidal forcing could be used in principle, but is usually impractical in chemical process systems [3].

The relevent equations are readily derived. The system transfer function is defined by

$$G(s) = \frac{Y(s)}{X(s)} = \frac{\int_0^\infty y(t)e^{-st}dt}{\int_0^\infty x(t)e^{-st}dt} \tag{7}$$

where x(t) and y(t) are the input and output functions, respectively. If the Laplace variable s is replaced by $j\omega$ one obtains

$$G(j\omega) = \frac{\int_0^\infty y(t)e^{-j\omega t}dt}{\int_0^\infty x(t)e^{-j\omega t}dt} \tag{8}$$

Now, if the system input is a pulse, the integral becomes

$$G(j\omega) = \frac{\int_0^{T_o} y(t)e^{-j\omega t}dt}{\int_0^{T_i} x(t)e^{-j\omega t}dt} \tag{9}$$

since the values of y(t) and x(t) are zero after some finite time (T_o and T_i respectively). Expanding the complex exponential by the Euler relation makes it clear that the integrals are readily evaluated with standard quadrature methods (*e.g.*, trapezoidal rule)

$$G(j\omega) = \frac{\int_0^{T_o} y(t)\cos(\omega t)dt - j\int_0^{T_o} y(t)\sin(\omega t)dt}{\int_0^{T_i} x(t)\cos(\omega t)dt - j\int_0^{T_i} x(t)\sin(\omega t)dt} \tag{10}$$

Specialized quadrature methods are available [6] that give more accuracy at high frequencies. At each frequency of interest, the integrals are evaluated to obtain the complex number G(jω), from which the amplitude ratio and phase angle of the system are obtained

$$AR = |G(j\omega)| \tag{11}$$

$$\phi = \measuredangle G(j\omega) \tag{12}$$

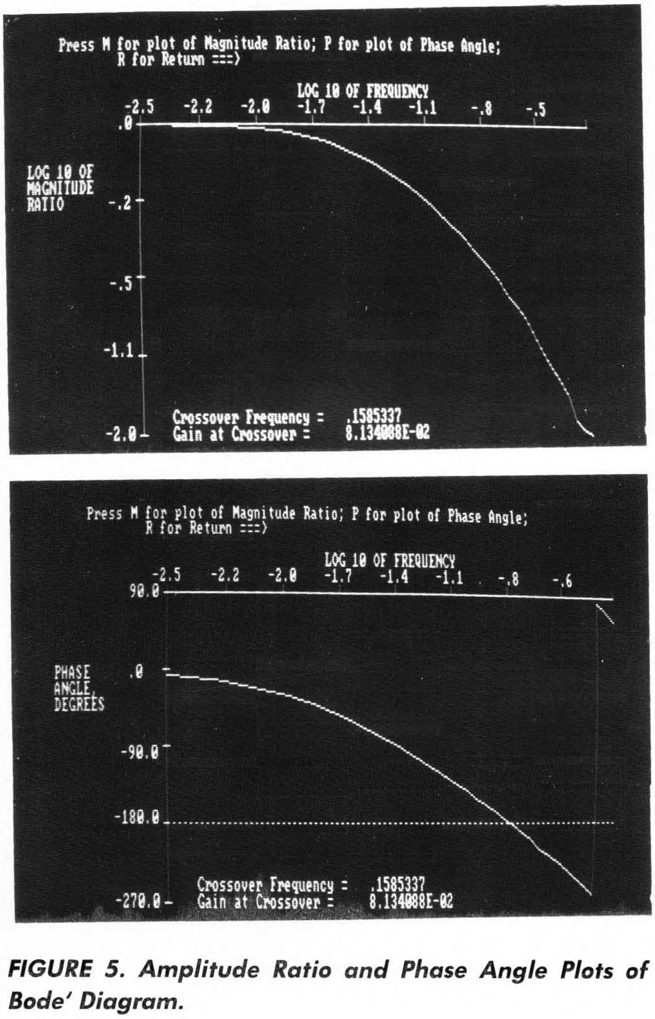

FIGURE 5. Amplitude Ratio and Phase Angle Plots of Bode′ Diagram.

Note that this involves a *lot* of calculation. Hand calculation of frequency response data from pulse test results is not practical, so any exercises involving pulse testing must involve computer data analysis.

The pulse test data analysis routine provided in the control systems design package may be used either with pulse test data generated by the open loop simulator, or data supplied from an external source (another simulation, or actual experimental data). The numerical integration method used combines trapezoidal rule at low frequencies, and piecewise linear approximation [6] at high frequencies. The output is presented on the screen in the form of a Bode′ plot, and can also be printed in tabular form. Figure 5 shows the Bode′ plot for the example system. It compares. closely with the analytic results presented in Smith and Corripio. It should be noted that the time required for the analysis may be several minutes even in compiled BASIC.

CONTROLLER DESIGN: FOPDT CORRELATIONS

A large number of studies, beginning with the classic works of Ziegler and Nichols [9] and Cohen and Coon [10], have investigated control of systems described by the FOPDT model. In each case, the quality of feedback control with various controller parameter values was determined. The earlier workers used quarter-decay ratio as their definition of good dynamic response, while more recent studies have used integral performance criteria as objective functions in determining the best parameter values [11]. In all cases, the ultimate result is a set of formulas that relate the gain (K_c), integral time (τ_I), and derivative time (τ_d) for proportional, proportional-integral, or proportional-integral-derivative controllers to the FOPDT model parameters (K, τ, and t_o). The premise is then that these optimum controller settings for a FOPDT process will yield similarly good control when applied to a process which can be appoximated by the FOPDT model.

The time domain controller tuning portion of the design package computes the values of the controller parameters for either P-only, PI, or PID controllers. Three correlations are reported: the classic Ziegler-Nichols and Cohen-Coon settings, and the settings of Lopez *et al* [11] based on the integral absolute error (IAE) performance index. Since the calculation of the controller settings from the FOPDT model parameters is rather trivial, students can readily be assigned to hand-calculate settings from any of the numerous other tuning formulae [3]. Further, it is instructive to compare the results for a specific tuning correlation, but based on alternative FOPDT model fits. Figure 6

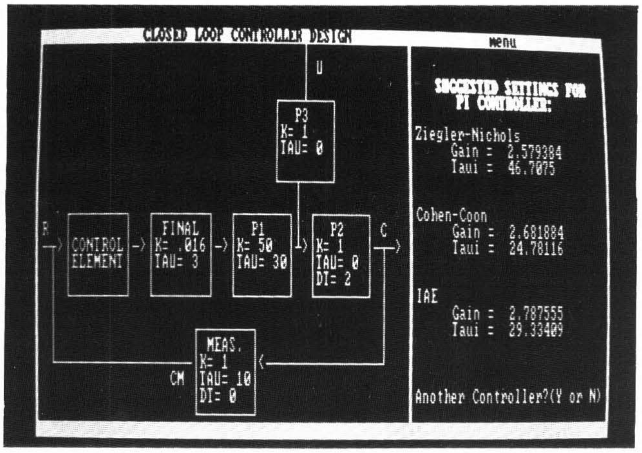

FIGURE 6. Closed Loop Block Diagram and PI Controller Settings Display.

shows the PI controller settings for the example system.

CONTROLLER DESIGN: FREQUENCY DOMAIN

The frequency response for the open loop system can be used directly to compute controller settings. Ziegler and Nichols [9] related the "optimum" controller settings to a pair of parameters readily obtained from the system Bode' plot: the crossover frequency (the frequency at which the phase angle reaches –180 degrees), and the "ultimate gain" (the inverse of the open loop gain at the crossover frequency). Stability considerations in the frequency domain indicate that if the loop were closed with a proportional controller, the closed loop system would become unstable for any controller gain greater than the ultimate gain [5]. The Ziegler-Nichols controller settings give controller gains which are roughly half the critical value, and integral and derivative times correlated to the crossover frequency. These relations are presented in virtually all introductory control texts [3,5,6,7,8]. The control system design program finds the crossover frequency and ultimate gain from the system Bode' plot, and reports the controller parameters.

CLOSED LOOP SIMULATION

In order to evaluate the actual performance of a control system, a controller must be added to the open loop system, and the closed loop system simulated. Figure 6 shows the resulting block diagram. The student is prompted to specify a controller type, and is permitted to choose one of the controller design methods incorporated in the design package (if the necessary open loop tests and data analysis have been carried out), or to specify values for the individual controller parameters. The latter option allows use of other design methods. It also permits empirical optimization of the controller for the particular system under investigation.

Either set point or disturbance inputs can be perturbed, and the user is allowed to specify either a pulse or step input. The resulting response is plotted on the screen, and the value of the integral absolute error (IAE) performance criterion is displayed to provide an objective measure of performance. Figure 7 shows the results obtained with the example system with P only, PI, and PID controllers based on the Ziegler-Nichols FOPDT design procedure.

A typical assignment using the closed loop simulator is to compare the performance obtained with various controllers and various controller tuning formulae, and then to investigate the effect of varying the controller parameters from the values determined by the best tuning correlation. This emphasizes the point that the various empirical correlations are normally good starting points in tuning a controller, but will only by chance be optimal.

CONCLUSIONS

The control systems design package described herein has proved to be quite effective in conveying basic feedback control concepts to undergraduate students. Furthermore, the students have responded very positively, both because of the opportunity to work with the computer, and because the program eliminates a great deal of tedium compared to hand calculations of controller design and performance.

Enhancements of the program are being planned. One will permit the student to be provided with a "black box" process rather than one specified in terms of loop transfer functions. The student can then be assigned to identify the *unknown* process by step and/or pulse testing and use the results to design a control

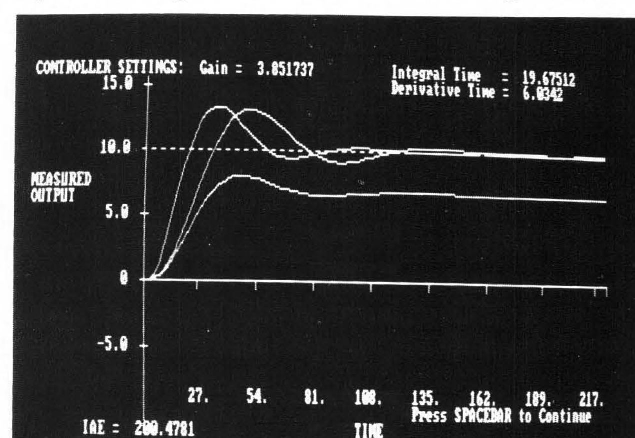

FIGURE 7. Proportional, PI, and PID Controller Performance Comparison.

system. Optional "noise" on the measured output may also be added to improve realism. The addition of an optional feedforward controller for the disturbance is also being considered.

Copies of the program (on 5 1/4 inch MS-DOS formatted diskette) and user documentation are available for $15 to cover duplication and postage. The program is supplied as executable files (compiled using the IBM BASCOM compiler), but BASIC source files are included as well.

ACKNOWLEDGEMENT

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ChE book reviews

NUMERICAL HEAT TRANSFER

by Tien-Mo Shih
Hemisphere Publishing, NY; 563 pages (1984)

Reviewed by
Michael F. Malone
University of Massachusetts

This is a lengthly book consisting of fifteen chapters in four parts. Part I is entitled "Preliminaries" and consists of the four chapters: 1. "Numerical Methods Used in Heat Transfer (I)," where finite difference and the finite element are introduced, 2. "Numerical Methods Used in Heat Transfer (II)," where a more extensive discussion of the Galerkin and Collocation methods appears, 3. "Numerical Methods Used in Heat Transfer (III)," that discusses higher-order finite elements, integral method and perturbation solutions, and 4. "Numerical Properties of Various Discretization Schemes."

Part 2 describes "Fundamental Heat Transfer Modes" in the chapters: 5. "Heat Conduction," 6. "Laminar Forced Convection: Hydrodynamic Boundary Layer (I)," 7. "Laminar Forced Convection: Hydrodynamic Boundary Layer (II)," 8. "Streamwise Diffusive Flows," 9. "Transport of Energy and Species," and 10. "Radiation."

Part 3 consists of three chapters on "Important Heat Transfer Phenomena": 11. "Laminar Free Convection and Mixed Convection," 12. "Introduction to Turbulent Flows," and 13. "Introduction to Combustion Phenomena."

"Numerical Analyses" is the fourth and final part made up of two chapters: 14. "Spaces and Error Bounds," and 15. "Comparison of Finite-Difference Method and Finite-Element Method."

There are also three appendices.

This book is detailed in its coverage of numerical method and examples; the literature references are concentrated largely in the 1970's and early 1980's. In some areas, such as the coverage of stiff, coupled, convective-diffusion models in Chapter 8, the material provides a welcome addition and summary of techniques such as upwinding in the Galerkin finite element method. However, there is a less than adequate treatment of transient problems using modern integration packages such as Gear's method to solve the evolution problem, although there is a discussion of the well-understood numerical instabilities and/or inconsistencies introducted by traditional explicit or explicit-implicit schemes for the initial-boundary value problem in Chapter 4.

This book could be used as a source of examples in a course in heat transfer or numerical methods. It would seem unsuitable as a textbook for either however, because of its restricted treatment of numerical methods on the one hand and because of its lack of the necessary perspective on the role of analytical methods and physical property measurements in heat transfer on the other.

The individual sections of the book are clearly written, but are heavy in detail at the expense of perspective. The printing is carefully done and the book seems to be relatively free of typographical errors. □

ChE class and home problems

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

A PROBLEM WITH COYOTES

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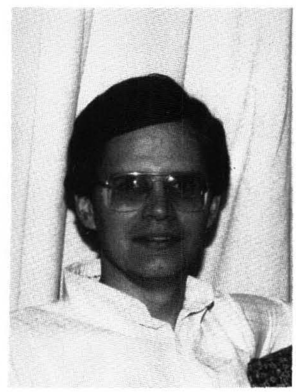
As a student in a graduate reaction engineering course, I was assigned the task of creating and taking a final examination for the course.* In our class discussion of reactor stability we had briefly addressed limit cycle behavior and its representation using phase-plane plots. This was the third instance in a matter of months that I had heard reference made to limit cycle behavior. The topic had also been broached in a departmental seminar and in another class. However, in each case the speaker did not have time to elaborate on this intuitively puzzling phenomenon. Hence, it seemed that a problem involving this stability concept would be interesting to the imaginary student taking my test.

A microbial predator-prey interaction model that I had been exposed to in a biotechnology course provided an attractive starting point, mostly due to its simplicity. However, I chose to apply the microbial model to a mammalian system, with the thought that such a macroscopic system would be easier to visualize. In an ancillary question, I observed that I had applied a simple model to a complex system and called upon the student to critique the model's construction and to propose possibilities for its improvement. The question and its solution follow.



Mark A. Young is currently a graduate student at North Carolina State University. He earned a liberal arts degree from Duke University in 1975 and a BS in chemical engineering from N.C. State in 1984. His research interests include biochemical engineering and transport phenomena. Any of his time not devoted to his wife or to engineering is generally spent listening to (and learning to play) traditional American and British music.

PROBLEM

While working in Arizona as a petroleum engineer, you are befriended by a sheep rancher who lives down the road. One afternoon the rancher seeks your advice on a problem. Recently his flock has been plagued by coyote attacks. In fact, in recent years so many lambs have been lost to coyotes that his flock is decreasing in size, a situation resulting in significant economic hardship. An acquaintance of his at the FCX has offered to trap and destroy coyotes in his region. The fee, however, is exorbitant. Nevertheless, the rancher is tempted to try the measure in hopes of expanding the sheep population.

You vaguely recall reading about the Lotka-Volterra model of predator-prey interactions during your university days. Leafing through an old book*, you find the following equations for the model

$$\frac{dn_1}{dt} = an_1 - kn_1n_2$$

$$\frac{dn_2}{dt} = -bn_2 + qkn_1n_2$$

*For a discussion of this assignment, see Felder, R. M., "The Generic Quiz: A Device To Stimulate Creativity and Higher-Level Thinking Skills," *Chemical Engineering Education*, 19, 176 (1985).

*Bailey, J. E. and Ollis, D. F., *Biochemical Engineering Fundamentals*, [2nd Ed.] New York: McGraw-Hill Book Co., 1986.

where n_1 = prey population
n_2 = predator population
a,b = specific growth rate constants for prey and predator respectively ($time^{-1}$)
$n_1 n_2$ = product of predator-prey populations; proportional to the frequency of predator-prey encounters
k = proportionality constant; represents both the fraction of predator-prey encounters resulting in death of the prey and the rate of decrease in prey population per kill ($time^{-1}$ $coyote^{-1}$)
q = proportionality constant; represents the amount by which predator population increases per kill (coyote $sheep^{-1}$)

The book also states that the model may be expressed as

$$\left(\frac{y_1}{\exp(y_1)}\right)^b \left(\frac{y_2}{\exp(y_2)}\right)^a = \exp(c)$$

where

$$y_1 = \left(\frac{n_1}{n_{1s}}\right) \qquad y_2 = \left(\frac{n_2}{n_{2s}}\right) \qquad c = \text{integration constant}$$

and the steady state solutions, n_{1s} and n_{2s}, are

$$n_{1s} = \left(\frac{b}{qk}\right) \qquad n_{2s} = \left(\frac{a}{k}\right)$$

1. Derive the second form of the model beginning with the first.

2. The trapper estimates that his operation could provide a 38% reduction in the coyote population. Assuming the following values for model parameters, would you recommend the trapping operation based upon the Lotka-Volterra model? In your analysis consider the time dependence of the sheep population both before and after the proposed trapping operation. Summarize your findings using phase-plane plots.

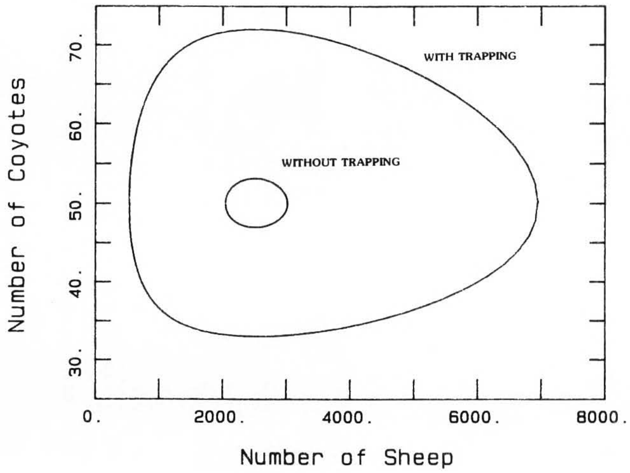


FIGURE 1. Predator/Prey Population Cycles

A microbial predator-prey interaction model that I had been exposed to in a biotechnology course provided an attractive starting point, mostly due to its simplicity.

Data: $a = 5 \times 10^{-3}$ day^{-1}
$b = 5 \times 10^{-4}$ day^{-1}
$k = 10^{-4}$ day^{-1} $coyote^{-1}$
$q = .002$ coyote $sheep^{-1}$
n_1 (initial) = 2350 sheep
n_2 (initial) = 53 coyotes

3. What assumptions have been integral to your analysis which might affect the validity of your results? How might you modify the model to increase its applicability for this situation?

SOLUTION

1. The derivation is easily performed and is briefly outlined by Bailey and Ollis (p. 872).

2. The behavior of the two populations over time may be represented in a phase-plane plot, which could be generated by either of two means: The second form of the model could be solved for y_2 for a selected y_1, or the coupled equations could be solved directly via a numerical technique. The highly nonlinear nature of the second model expression makes determination of its roots via conventional numerical techniques quite difficult. An additional disadvantage to this approach is that one cannot associate a time with a given position on the plot, which might be helpful in an application such as this. Consequently, the coupled equations were solved using a Runge-Kutta routine. The output appears in Table 1 (next page).

The phase-plane plot appears in Figure 1. Shown are the predicted population cycles for the situations with and without the decrease in coyote population. The stable population of 2500 sheep and 50 coyotes is indicated. From the graph and the data one would deduce that the sheep population is currently about halfway through the declining phase of its cycle, which correlates with the rancher's account of dwindling numbers of sheep in recent years. Although the population is cyclic, it is relatively close to the stable population. On the other hand, after the elimination of 20 coyotes, the range of the cycle becomes enormous. If this cycle were followed, the sheep population would soar to over 6500 for a period but then plummet to below 1000 for over three years. To determine whether the trapping operation would lead to a net increase in the average sheep population, one can time-average the data for both situations:

$$\frac{\text{average number of sheep}}{\text{year}} = \frac{1}{T}\int_0^T n_1 \, dt$$

where T = the cycle period

Taking this average using the trapezoid rule yields

average population without trapping = 2500 sheep
average population with trapping = 2500 sheep

Thus, in either case the population oscillates around the same value. Consequently, the rancher would be unwise to pay for trapping the coyotes. Reduction of the coyote population would not increase his average flock size but would introduce huge cyclic extremes in population, which would exacerbate his economic difficulties.

3. Clearly, many changes could be made to the model which would improve its applicability to this situation. Several suggestions are listed below.

a) The model assumes that predators have only one food source (the prey species), which is not realistic in this situation. A term could be added to represent the lumped effects of alternative food sources.

b) The model assumes that prey die only due to predation. A term could be added to represent the lumped effects of other means of death, *e.g.* disease, old age, and severe weather.

c) The model bases reproduction rate upon the number of individuals present. This is reasonable for species subject to asexual reproduction, but for mammals growth would more logically be proportional to the number of pairs , $n_1/2$. Even better, reproduction could be modeled as being proportional to the number of interactions between members of the opposite sex, $(n_1/2)^2$. The model would then become

TABLE 1

Population Dynamics With Trapping

TIME (years)	SHEEP	COYOTES
0.0	2350.0	33.0
0.7	3578.1	33.7
1.4	5193.9	37.0
2.1	6641.0	44.0
2.7	6780.3	54.8
3.4	5226.8	65.6
4.1	3246.9	71.4
4.8	1880.3	71.4
5.5	1144.7	67.9
6.2	779.2	62.8
6.8	606.1	57.3
7.5	539.7	52.0
8.2	545.6	47.2
8.9	618.9	42.8
9.6	776.4	39.1
10.3	1059.3	36.1
11.0	1541.8	34.0
11.6	2335.6	33.0
12.3	3557.1	33.7
13.0	5169.5	36.9
13.7	6626.6	43.9
14.4	6791.7	54.6
15.1	5256.2	65.5
15.8	3272.1	71.4
16.4	1894.9	71.5
17.1	1152.1	67.9
17.8	782.8	62.9
18.5	607.8	57.4
19.2	540.1	52.1
19.9	545.1	47.2
20.5	617.3	42.9
21.2	773.3	39.2
21.9	1054.0	36.2
22.6	1532.9	34.0
23.3	2321.3	33.0
24.0	3536.2	33.7

Population Dynamics Without Trapping

TIME (years)	SHEEP	COYOTES
0.0	2350.0	53.0
0.7	2195.0	52.4
1.4	2091.0	51.5
2.1	2044.3	50.3
2.7	2056.1	49.2
3.4	2124.7	48.2
4.1	2245.2	47.4
4.8	2408.3	47.0
5.5	2596.8	47.0
6.2	2784.2	47.5
6.8	2935.6	48.4
7.5	3015.8	49.5
8.2	3002.2	50.8
8.9	2896.3	52.0
9.6	2724.2	52.8
10.3	2525.2	53.2
11.0	2336.6	53.0
11.6	2185.1	52.3
12.3	2085.3	51.4
13.0	2043.1	50.3
13.7	2059.4	49.1
14.4	2132.2	48.1
15.1	2256.4	47.4
15.8	2422.1	47.0
16.4	2611.6	47.0
17.1	2797.6	47.5
17.8	2944.7	48.4
18.5	3018.2	49.6
19.2	2997.2	50.9
19.9	2885.0	52.1
20.5	2709.4	52.9
21.2	2509.9	53.2
21.9	2323.4	52.9
22.6	2175.5	52.3
23.3	2080.0	51.3
24.0	2042.3	50.2

$$\frac{dn_1}{dt} = a\left(\frac{n_1}{2}\right)^2 - kn_1n_2$$

d) The model assumes an environment shielded from external intervention, *e.g.* urban growth displacing coyotes from an adjacent region into your region. Such factors would be difficult to incorporate into the model explicitly, but their existence adds to the uncertainty of the results.

e) The model predicts unbounded prey growth in the absence of the predator. This is clearly unrealistic as other limits to growth exist, *e.g.* food supply and land area. The specific growth rate term could be modified to approach zero when the population reaches the maximum number which the environment can maintain. For example, if the food supply (F) were taken to be the limiting factor in the absence of predators, the model might become:

$$\frac{dn_1}{dt} = \left(a - \frac{b}{c + F}\right) n_1 \qquad \text{where } \left(\frac{b}{c}\right) = a$$

An additional equation for how F changes with n_1 and n_2 would also be required.

f) The parameter estimates are clearly a large source of uncertainty. A sensitivity analysis could be done on the parameters, and improved estimates could be sought for those having the greatest impact.

For example, the parameters of most interest are those determining the steady state sheep population, *i.e.*, b, q and k. A 20% increase in the estimate of b results in a comparable increase in the steady state population, but the average coyote population is unchanged. Similarly, decreases in q elevate the prey population without affecting the predator population. If the estimates for k and q were increased and decreased by 20% respectively, the prey population would increase by 25.0%, while the predator population would decrease by 16.6%. However, these rather modest changes in parameter and steady state values are accompanied by drastically different behavior in the phase plane representation of population dynamics. As seen in Figure 2, a totally different vision of the effects of trapping emerges when these parameter changes are made. Indeed, even the qualitative trends are inverted, with the larger oscillations in population occurring *before* the trapping operation.

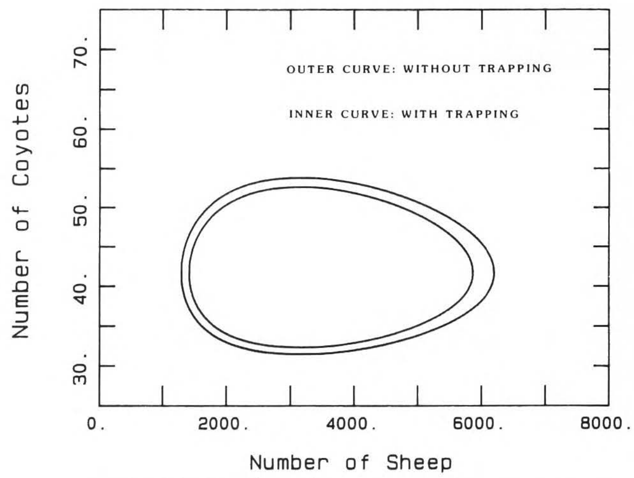


***FIGURE 2.** Predator/Prey Population Cycles*

CONCLUSION

Counterparts to the undamped oscillation examined here in a biological context are readily found in chemical engineering applications. In both cases competing effects may be identified as the underlying cause of the oscillation. In the biological example, the rate of increase in prey population is enhanced by enlarged population size and decreased by encounters with the predator species. Conversely, the growth rate of the predator population is negatively affected by increases in its magnitude and benefited by increased encounters with the prey.

Conceptually similar phenomena may be identified in a temperature-controlled CSTR in which an exothermic decomposition reaction occurs. The rate of heating is elevated by increases in reactant concentration and reactor temperature. Heat exchange coils in the reactor constantly remove heat at a rate proportional to the difference between the reactor and cooling-water temperatures. In a simple control scheme, additional cooling capacity would be engaged whenever the reactor temperature exceeds the setpoint temperature. The rate of the added cooling would be proportional to the deviation from the desired temperature.

Hence, for such a reactor, high temperatures invoke a high cooling rate with concomitant decreases in the reaction (heating) rate, and the temperature falls. In contrast, low temperatures result in low cooling rates and low reaction rate constants. Resulting increases in reactant concentration raise the reaction (heating) rate, and the temperature rises. For certain combinations of system parameters, these competing effects generate limit cycles very similar to those displayed by the predator-prey example. However, a noteworthy distinction may be made between the two types of oscillations: The position of the predator-prey population cycle in the phase plane depends upon the initial population sizes, but for the chemical reactor, the location of the cycle is independent of initial reactor temperature.

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ChE international

CHEMICAL ENGINEERING EDUCATION AND PROBLEMS IN NIGERIA

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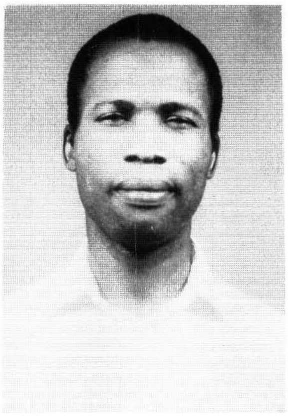
THE PROBLEMS OF chemical engineering education in Nigeria, as in other developing countries, are closely tied to economic conditions and its state of industrialization. Since it emerged as a sovereign state, Nigeria has experienced a "pre-austerity" period, followed by an "austerity" (1982 till present) period. The second period is when the government realized it had a limited and fast-dwindling foreign exchange, and it imposed stringent measures to protect it. However, problems with chemical engineering education remained identical in both periods. For example, in the pre-austerity time the government had a sufficient budget to establish modern chemical engineering departments and to obtain laboratory equipment. Nonetheless, maintenance and efficient use of these facilities was not achieved, as Abdul Kareem [1] and Silveston [5] discussed. On the other hand, educational institutions that introduced chemical engineering programs during the present austerity period do not have laboratory equipment and other facilities due to a shortage of funds.



Ogbonnaya Charles Okorafor graduated with BSc (1977) in chemical engineering at the University of Lagos. After graduation he worked for two years as a research engineer with the Federal Institute of Industrial Research, Oshodi Lagos. He received his MASc (1980) and his PhD (1982) from the University of British Columbia, Vancouver, and returned to Nigeria as a Lecturer at the department of chemical engineering, University of Port Harcourt. His present research interests include crystallization and process engineering.

PRESENT STATE OF ChE EDUCATION

In Nigeria there are two types of undergraduate programs, although they are essentially the same in actual chemical engineering course content. The four-year program is mainly for students with the General Certificate of Education (G.C.E.) A-level diploma in the three foundation subjects (chemistry, physics, and mathematics). The G.C.E. A-level is probably equivalent to a two-year post-high school study in a community college as found in U.S. and Canada. The other is a five-year program for candidates with a high school diploma (West African School Certificate or G.C.E. O-level passes in five subjects, including the foundation subjects). Candidates with G.C.E. A-level are exempted from the matriculation examination and are expected to enroll in the second year of the five-year engineering program. Students with G.C.E. O-level sit for the matriculation examination organized by the Joint Admissions and Matriculation Board (J.A.M.B) for all the accredited universities in the country, held every year on the last Saturday of April. Successful candidates are placed in the schools of their choice by JAMB and enter the first year of the five-year program.

In Nigeria there are two types of undergraduate programs, although they are essentially the same in actual chemical engineering course content.

There are presently twenty-four universities accredited by JAMB in the country. Sixteen of them belong to the Federal Government, while the remaining eight are owned by various state governments. Of these, only nine institutions have chemical engineering departments (JAMB Brochure 1985-86). Just four of the nine institutions have begun the graduate programs.

The chemical engineering courses are introduced in the second year of the five-year undergraduate education. From the second year to the fourth year, inclusive, emphasis is placed on understanding the following transport phenomena (heat transfer, mass transfer, and fluid mechanics), thermodynamics, particulate systems, separation processes, chemical engineering kinetics and catalysis, chemical reaction engineering, industrial chemistry, polymer science and technology, principles of plant design, chemical engineering laboratory and chemical engineering analysis. Subjects like electrical technology, strength of materials, metallurgy, science of matrials, computer programming, mathematics, chemistry, physics, and humanities are taken from other units of the institutions. Only a few courses, such as process dynamics and control, process modeling and optimization, introduction to biochemical engineering, management and law, are taken in the fifth year in order to provide ample time for the student to tackle the two important final year projects. The projects are the chemical engineering research (an individually supervised research on any chemical engineering topic of national interest chosen by the student), lecturer group, and the chemical engineering design project (the design of an integrated process by a group of students).

Few institutions in Nigeria (and only the pre-austerity ones) have well-equipped, well-maintained and up-to-date chemical engineering laboratories that include unit operations, reaction engineering, and biochemical engineering laboratories. Even these institutions do not have process control laboratories. Computers (digital, analog, and hybrid) are effectively exploited in just a few chemical engineering departments.

Another important feature of the undergraduate curriculum is the compulsory nine months industrial attachment for the students. This is one of the requirements for a department's accreditation by the Council of Registered Engineers of Nigeria (COREN). Some institutions operate a straight academic year industrial attachment while others split the nine months into three and attach the students to industries during the three months summer vacation of the second, third and fourth years.

DIFFICULTIES IN ChE EDUCATION

Nigeria's problems include: a shortage of technical know-how (including a shortage of faculty, inadequacy or lack of support services, shortage of teaching and research equipment, inadequate or non-existent research funding, lack of administrative experience, negative attitude towards work, and isolation from centers of technical activities), insufficient funds, and lack of supporting industries. The first problem has been detailed and possible solutions advanced by Abdul-Kareen [1] and Silveston [5].

The funding problem is an old one in Nigeria. Even in the "boom" years the percentage of the national budget allocated to education at all levels should have been higher than it was. The present severe underfunding is compounded by the political decision that students should have a tuition-free university education.

A lack of supporting industries means that many services which promote the quality of engineering education, such as regular maintenance of laboratory equipment, consulting opportunities for the engineering faculty members, training of laboratory technicians and students, are missing.

Few institutions in Nigeria have well-equipped, well-maintained and up-to-date chemical engineering laboratories that include unit operations, reaction engineering, and biochemical engineering laboratories.

During the boom period, Nigeria imported industries with the hope that some modern technology would be transferred to her. This, however, has not happened. These industries have been "import substitution"; that is, raw materials, spare parts and other things are imported. The duty of the imported industry then reduces to mixing, assembling and packaging. Foreign industries have not been willing to transfer their up-to-date technical know-how. The technical people assigned to absorb the modern technology that is made available are often not knowledgeable or competent enough to do so effectively because their selection may have been carried out for reasons of political expediency or even through chicanery.

The lack of supporting industries causes additional burdens with respect to training. All students are required to spend at least nine months at some factory for training. Unfortunately, many students return with little or no practical experience. Either they are not received properly by the industrial organization through the assignment of challenging and responsible duties, or the students discover that their chemical engineering background does not coincide with what they are presumably being trained for. Some students lose interest in pursuing an industrial career after graduation. Instead they choose non-technical, office-type work, or go on to graduate studies, provided that sufficient interest, a good first degree and funds are available to them. Furthermore, when the few industries we do have run into technical problems which require research and/or development, authorities in both government and industry turn to the more expensive foreign experts for help. They hesitate to make use of the talents of their own researchers and scholars (who are in most cases educated in the very same countries from which the technical assistance is sought).

Student population problems also seem to originate from a lack of healthy industries as well as a lack of technical training centers. High school graduates turn to colleges and universities as their only route to success and a rewarding future. However, the size and facilities of the institutions are limited and in most cases can accommodate a mere 5-10 percent of the applicants. The demand for higher education tends to overcrowd all institutions and especially the engineering schools, which are among the most popular ones. Faculty-student ratio is reduced and this causes deterioration of the quality of engineering education, as Murti and Murray-Lasso [3] pointed out. Another problem which places more of a burden on faculty members is the relatively weak foundation of entering students in chemistry, mathematics and physics. Although this problem could be solved if only the best students at the matriculation examination are selected for admission, a government policy requires preferential admission for candidates from the so-called "educationally less developed" areas. The result is poorly prepared students in our classes.

FUTURE PROSPECTS AND SUGGESTIONS

Even though the government has recognized the technological education problem, the present approach does not offer relief. Proliferation of ill-equipped institutions is not a solution. What *is* needed is:

- **Improved technical training along the lines proposed by Abdul-Kareem and Silveston [1]. In addition, governments should discontinue the 'federal-character' or 'state character' policy in staff recruiting. A situation where a foreigner is preferred over a more-qualified fellow citizen, even one from a different section of the country, is an anathema.**
- **Improved relations between university communities and industrial centers. This would make industrial administrators and government policy makers aware of the potential talents available in Nigeria's own institutions. It would permit faculty members to gain practical experience through short-term or long-term industrial leaves-of-absence. The lecturers would also become conscious of chemical engineering problems which industries are facing and could, in turn, modify the contents of their courses and their educational programs accordingly. A closer relationship would open new avenues for chemical engineering students to get worth-while, on-the-job technical training during their years at the university. Since most industries in Nigeria are transnationals with chemical engineers active in the top echelons of management, perhaps they can help by urging branch plants to set up research and development departments and encouraging these departments to work together with universities.**
- **Effective research institutes and centres which can cooperate with our academic institutions and assist our industries with problems such as alternative raw materials for industries, energy resources planning, utilization and management, design and construction of industrial plants, pollution abatement, greater agricultural productivity, and food storage, to name the most obvious ones. Effective research institutions could make proper use of experts from other countries and attract Nigerian researchers and scientists who are living abroad towards solving problems of their country without having to return home. Funds for industrial research centers could come from government or from some of our own men of wealth, who now seem to squander their riches on frivolities.**
- **Foreign Support: Grants now offered for faculty fellowships by the U.S., Canada and Great Britain need to be redirected towards more urgent needs such as teaching and research equipment and books for our libraries.**

REFERENCES

1. Abdul-Kareen, H. K. (1983) "ChE Education in the Third World—Need for International Cooperation," *CEE*, Spring 1983, p. 79-82.
2. J.A.M.B. Brochure 1985-86 Session (Guidelines for Admission to First Degree Courses in Nigerian Universities).
3. Murray-Lasso, M. A. (1972) "Engineering Education in Mexico," *IEEE Trans. Educ.* E-15 (4), 214-219.
4. Murti, (1972) *Ibid.*
5. Silveston, P. L. (1983) "ChE Eduation in the Third World—North American Assistance," *CEE*, Spring 1983, p. 78. □

REVIEW: Polymer Systems

Continued from page 33.

steps in the development of a final product.

After the general treatment outlined above, the student is introduced to specific polymers, their characteristics, and their uses in a chapter devoted to addition type polymers and another chapter on condensation type polymers. The final chapter deals with various analytical methods used in polymer characterization and identification. This serves as a brief introduction for the chemical engineer to some of the most common techniques likely to be encountered during making or using polymers.

The appendices are an especially useful feature of this book as they give literature sources, a number of laboratory exercises, and finally, an index of properties for the most common polymers. The latter may be a convenient reference for the student after graduation.

While the number of textbooks in this area is much greater than it was in 1970, the second edition of Rodriguez should be given careful consideration when selecting a text. Its price is reasonable at $29.95. □

ELEMENTARY PRINCIPLES OF CHEMICAL PROCESSES, 2nd Edition

by R. M. Felder and R. W. Rousseau
John Wiley & Sons, Somerset, NJ $43.95 (1986)

Reviewed by
Dady B. Dadyburjor
West Virginia University

Since this is the second edition of one of the more popular books for an introductory course in chemical engineering for sophomores, this review will try to address two audiences—those who are familiar with the first edition and who wish to know how it differs from the present one, and those who wish to compare this text with others on the same topic. At the start, it is fair to point out that at this university the text probably receives a more rigorous workout than at many other places since it is the basis for the major portion of two semester-long courses; consequently, many of the points of discussion may not even be noticed by those moving through the text at a more hurried pace.

For those unfamiliar with the book, it starts out with a few preliminaries, reminders of topics covered in previous courses, then moves to the fundamentals of material balances. The treatment is extremely thorough and step-by-step, from non-reacting, single species, single units to multiple reactions, multiple units with recycle, bypass, and (new to this edition) purge. Then follow the constitutive equations for relations in one or more phases, with examples showing their use in solving balances with data that is easier to obtain. The section on energy balances builds on material covered previously, and first shows how the simple forms of the general equation can be derived. This is followed by the constitutive relations defining specific heats, heats of reaction, heats of phase change, and heats of mixing, and their use in energy balances. Then come general chapters on computer-aided calculations (new) and transient processes. Finally, there is a set of case studies, different from those in the first edition. Each case study is a good example of a set of problems which can be either treated after all of the book material is covered or in discrete increments during the course. Either way, in each case study there are one or two open-ended problems which serve as "capstones" for all of the material covered. At the end of every chapter there are numerous problems, with a good mix of calculator- and computer-type solutions. Liberally sprinkled throughout the chapter are a set of "Test Yourself" exercises with solutions, verifying that the student has understood the concepts, and a set of "Creativity Exercises" (new) to challenge budding engineers. Each chapter also contains a good number of worked examples of a wide range of difficulty.

In my mind, there were only a few, minor, negatives in the first edition, and many of these have been improved upon in this work. A notable example is the section on bubble and dew points, which has been greatly expanded and improved. The more formal treatment of the degrees of freedom and its relation to the number of unknowns and the number of equations in a given system is most appropriate. There is also a much better treatment of the concepts of fractional conversion and stoichiometric coefficient. However, the treatment of the heat of solution with reference to an infinitely dilute standard state would be a good candidate for further expansion together with, perhaps, a worked example of significant difficulty. More significantly, in the treatment of material balances there is a new section on thermodynamic equilibrium that I believe the book could have done without. The parameter defined is not the Equilibrium Constant and will almost certainly lead to confusion in subsequent courses in thermodynamics, particularly with respect to equilibrium in multiple phases. Further, in the treatment of energy balances I am not particularly in favor of the Table format used, where component amounts and enthalpies in the inlet and outlet streams are listed. This is useful only after the numbers are obtained and does little to explain how this is done. I would rather see more extensive use of the diagrams of hypothetical steps in going from inlet to outlet conditions. Finally, in the treatment of transient balances, I would have liked to have seen a greater emphasis on problems requiring the solution of (simple) differential equations—for instance with semibatch operations—instead of a rehashing of integral batch analysis. I would also have liked to have seen more continuity between material balances and energy balance transient problems—for instance, the chemical reactor and batch distillation treated from the energy balance point of view.

These drawbacks are more than compensated by the many advantages of both editions of the book. It is written in a clear, direct, almost conversational style; a wide range of material is covered in relatively

Continued on next page.

few pages; and the coverage is systematic in its progression from simple systems to more complicated ones. Almost certainly, this book will maintain its leading role among its fellows. □

UNIT OPERATIONS OF CHEMICAL ENGINEERING, 4TH EDITION

by Warren L. McCabe, Julian C. Smith and Peter Harriot, McGraw Hill (1985), 960 pages, $53.95.

Reviewed by
A. H. Peter Skelland
Georgia Institute of Technology

Thirty years have passed since the publication of the first edition of this durable text, and its influence on the profession through succeeding editions and three decades of graduating seniors must have been profound. The second edition, published in 1967, reorganized the material in the first version into four main sections, *e.g.*, fluid mechanics, heat transfer, equilibrium stages and mass transfer, and operations involving particulate solids. This format, which has become one of the hallmarks of the book, has been retained through the third and fourth editions, published in 1976 and 1985, respectively.

Peter Harriott, mentioned in the preface to the first edition as one who reviewed a portion of that early manuscript, now becomes the third author of the revised fourth edition.

The authors have commendably resisted the temptation to expand the book further by merely adding new material; instead they have actually achieved a 6.6% reduction in pages to a total of 960. This has been accomplished by deletions which include most of the previous material on mass and energy balances (normally covered elsewhere in the chemical engineering curriculum), the entire chapter on phase equilibria (usually treated in thermodynamics courses), and, interestingly, the Ponchon-Savarit method of analysis for binary distillation, leaching, and liquid-liquid extraction processes. This involves elimination of the triangular diagram-delta point method and of the Ponchon (Janecke) diagrams in extraction. This, the authors contend, is because the procedure "is rarely if ever used in practice; for simple separations the McCabe-Thiele method is entirely adequate and for more complex separations computer methods are used." A bold move!

These deletions are countered by several additions, which include (for the first time) an excellent 21-page chapter on adsorption, expanded treatments of fluidization, packed bed heat transfer, and multicomponent distillation (which by now has reached a level of presentation that would probably enable superior students to perform plate-to-plate calculations). Further revision and reorganization are apparent in many areas of this familiar work.

An argument might be made for treating packed distillation columns in the chapter on distillation, instead of in the one on gas absorption. This would be on the grounds that distillation is characterized by essentially equimolal countertransfer, in contrast to gas absorption, which is an example of one-component mass transfer (one-way diffusion). This necessitates differences in rigorous formulation of the transfer unit expressions in the two cases, particularly for non-dilute systems.

The time has perhaps come to correct an important error that has curiously persisted through the second, third, and fourth editions; this occurs in citing the Friend and Metzner equation for heat transfer in turbulent flow in a smooth tube. The expression is Equation (12-62) on page 315, where a factor of 11.8 has been omitted from the second term in the denominator. Offered as a "more accurate analogy equation" for h, heat exchangers designed using the uncorrected equation would be seriously undersized.

Much of the current clamor for writing in SI units tends to overlook the fact that a great body of engineering literature already exists in either cgs or English units. Engineers must therefore retain facility with traditional unit-systems for easy access to the older literature, while becoming conversant with SI units for best use of the newer material and for present application. This dual need is well accomodated by the authors' decision to emphasize both SI and English units throughout the book.

The text is well stocked with problems for practice solution, 36% of which are new with this edition. The Appendices have been expanded by two, compared to the third edition, by the inclusion of the DePriester charts giving distribution coefficients in light hydrocarbon systems for low- and high-temperature ranges. The present reviewer believes that the book would have been enhanced by the inclusion of an author index, but a good 16-page subject index has been provided.

The drawings, printing, and binding all conform to the high standards we have come to expect in this series and, at $53.95, the text gives better value than most others in the field—certainly it should help more engineers get more jobs done than will most of its competitors.

When one includes the precursor of this text, *Elements of Chemical Engineering*, by W. L. Badger and W. L. McCabe, first published by McGraw-Hill in

1931, it is realized that Warren L. McCabe has provided textbook guidance to chemical engineers in a continuous and ongoing manner for more than half a century. The latest edition of this book constitutes a fitting memorial to his outstanding contributions to the profession. □

PROCESS REACTOR DESIGN
by Ning Hsing Chen
Allyn and Bacon, Inc., Publishers,
Boston, MA (1983) 545 pages

Reviewed by
Arland H. Johannes
Oklahoma State University

Textbooks on chemical engineering kinetics and reactor design have changed significantly in the past three decades as the Hougen and Watson approach shifted to a Levenspiel approach. This evolutionary change continues in this book by introducing numerical methods and computer solutions to complex chemical reactor design equations and problems. We expect that future texts in this area will follow this trend and use many of the more modern ideas and techniques presented in this book to solve industrial reactor design problems.

The text is suitable for a first undergraduate course in reactor design. The content is divided into eleven chapters with mathematical techniques reviewed briefly in the ten appendices. The author uses the molar extent of reaction (reaction coordinate method) as a bookkeeping and computational tool throughout the text. This method is introduced in the first two chapters on Fundamentals and Process Thermodynamics and is used extensively in the evaluation of kinetic data presented in Chapter 3.

After introducing the basic transport equations in Chapter 4, the author covers homogeneous systems by devoting a chapter to each of the four ideal reactors. In each chapter, isothermal, nonisothermal and multiple reactions are covered for each ideal reactor type. This is a particularly refreshing and logical presentation of the material.

The last three chapters cover heterogeneous reactor systems, nonideal reactors and design considerations. The heterogeneous reactor chapter covers each heterogeneous system including catalytic and fluidized bed reactors. Although this chapter is not written in great detail, it provides a good overview of these systems and a fairly good presentation of the design equations and mathematical techniques needed for modeling these systems. The nonideal chapter is very brief and barely covers problems typically encountered in industrial applications. The material in this chapter must be externally supplemented to provide coverage of nonideal systems.

The final chapter covers some of the major design and economic considerations in reactor sizing. This chapter also compares combination reactor systems and looks at selectivity and productivity.

In general, the material throughout the book is presented using vigorous mathematical development followed by numerous numerical example problems. Fourteen short computer programs are included in the text and are used frequently to solve the more complex problems. Some background in computer programming would be helpful to the student using this text but a solid mathematics background is absolutely required. Notation is straightforward and is consistent throughout the text. The end-of-chapter problems cover the material well and are suitable for homework, but the total number of these problems is fairly limited. The book is well written and the English is good, but at times a more general description would be more helpful than the step-by-step mathematical development.

In summary, this book is a useful teaching and reference text on modern reactor design. □

ChE books received

Microcomputers in the Process Industry, E. R. Robinson. John Wiley & Sons, Inc., Somerset, NJ 08873; 349 pages, $78.95, (1985).

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Basic Corrosion and Oxidation, Second Edition, by John M. West; Halstead Press, Somerset, NJ 08873; 264 pages, $44.95 (1986).

Modern Control Techniques for the Processing Industries, by T. H. Tsai, J. W. Lane, C. S. Lin; Marcel Dekker, Inc., 270 Madison Avenue, New York, NY 10016; 296 pages, $59.75 (1986).

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ChE IN THE FUTURE

Continued from page 17.

training. Or one can establish an internal school, like MacDonalds' Burger Tech. The company can offer short courses, either taught by employees or conducted by outside firms or local universities. Even courses for degree credit can be arranged, locally or by television. All of these things are being done—it is a big business.

But should this be necessary? A technical degree is supposed to certify competence to practice in the field and provide the necessary background for the recipient to function in a useful capacity while extending the knowledge into specialized areas on-the-job. No business would flourish by selling a product that the buyer had to modify extensively before being able to use it, even though sophisticated buyers often do add proprietary touches.

It is inefficient and costly for industry to try to substitute for the university. Including overhead and support personnel such as technicians, it costs about $200,000 per year to support a technical person in an industrial R&D organization. The lost-opportunity cost when these people either take instruction or provide it is even higher. We should expect a return of nearly $600,000 per year to result from their contributions. The net present value is even higher—one year of R&D work by a knowledgeable person working on new products or major product and process improvements is worth about $2 million. Looked at that way—and we do—it costs over $2 million per man-year for a research professional to do nonproductive work.

Let me hasten to add that we do believe in the value of continuing education to sharpen skills and enhance breadth of knowledge. We are willing to pay for an appropriate amount of it. We have no desire, though, to pay for remedial education, just as you do not want to teach students to read or count.

Hence the last three items in Table 4. Engineers should be taught to use fundamentals to solve problems and to be mentally prepared and motivated to use them. They should be prepared to reason effectively and draw logical conclusions using a quantitative approach. They should then be able to communicate well enough to explain their conclusions and reasoning effectively and to convince management or customers to act in accordance with the recommendations. And, of course, engineers should be willing and eager to learn.

ACTION ITEMS

Assuming that our goal is to expand the marketability of chemical engineers, we must ask several questions: What might be done to provide this kind of product? What kind of changes are possible, and who will make them? *Why* should they make them?

Table 5 lists six areas in which changes might be made. Each will be discussed in turn.

TABLE 5
Possible Actions

- CURRICULUM CHANGES
- STRUCTURED OPTIONS
- IMPROVED USE OF NEW TECHNOLOGY
- FORWARD-LOOKING TEXTBOOKS
- MORE EMPHASIS ON ADVANCED DEGREES
- CONTINUING EDUCATION

Curriculum

Howard Rase, in preparing the report of the Septenary Committee [2,3], devoted considerable space to recommendations on the curriculum. Some of them are listed in Table 6. We urge you to read that report if you have not already done so. The last four issues in the table deal with providing room in the curriculum without sacrificing the most important subjects or lengthening the undergraduate program.

Minor changes, where two or three courses are altered or eliminated in favor of others, will have little if any effect. If the product is to be a chemical engineer able to function in industry and adapt to a continually changing environment, that engineer must have not only a broad knowledge of scientific principles and techniques, but also some specialized knowledge about the particular technology in which he will be employed—biology, electronics, materials, chemical separations, statistics, and computer programming, to name a few.

The term "learning curve" has become such a cliché in the context of pricing strategy, project management and the like, that sometimes we forget its original use as a description of an individual's learning process. Acquiring and using new knowledge depends upon a host of connections among bits of information and also upon attitudes and concepts derived from experience. In four or five years of training, it is impossible to provide every student with every knowledge segment that will be useful. So what can be done?

First, eliminate duplication. Start with high school prerequisites. If you require calculus or chemistry, then expect the student to know it. If it has to be made up, since not all high schools are equally proficient and not all high school students are as studious as one might wish, then by all means teach remedial courses—but don't give credit toward the degree for them.

The next element of duplication that should be eliminated is the repetition between different departments of the university. Reinforcement is certainly needed for many subjects, but teaching thermodynamics in both chemistry and chemical engineering is really unnecessary. The remedy may require the faculties of different departments or colleges to work together to offer sections of, say, physical or organic chemistry that are slanted toward chemical engineers. I realize that this area is a problem in most universities, but it should be addressed.

The second point is to use computers more effectively—and I do not mean requiring more programming! A survey of our own engineers who have graduated within the last five years or so indicates that in many cases they feel they got too much of that. The real need, they think, is to integrate the computer into the course to such a degree that the added capability is channelled toward improving their judgment. All of the tedious hand calculations and shortcut techniques that used to play such a major role in chemical engineering courses should be abandoned. Instead

TABLE 6
Recommended Curriculum Changes*

- **Prepare for continual change with a broad range of fundamental knowledge.**
- **Provide some flexibility for a limited degree of specialization**
- **Provide room by**
  - **Eliminating duplication**
  - **Using computers more effectively**
  - **Combining courses**
- **Switch some organic chemistry to biochemistry and change physics to emphasize the solid state.**
- **Require modern biology, materials science, modern electronics, economics.**
- **Use specialized liberal arts courses.**

*From report of the Septenary Committee on the future of Chemical Engineering

students should learn to use problem-solving software to try cases and to clarify the fundamentals. This approach will require major investments in time, equipment, text writing, problem construction, and nearly every other phase of teaching. Not only would it make better engineers, but it could also allow some time to be cut from the curriculum to make room for other subjects.

The third and fourth points are different aspects of the same idea. By judicious selection of problems, experiments, and special requirements, a single course can cover several objectives. For example, oral presentations of results and review by English teachers of written reports can be part of laboratory

The second possible action, then, is the use of structured options. Many schools do this already, to a limited extent.

or unit operations courses. History could cover the history of science, government might discuss the need for a national science policy and the workings of government-sponsored research, language can feature original scientific papers, and philosophy can cover the development of scientific reasoning and thought.

There is some disagreement about how much of the curriculum should be devoted to distributional courses and the kind that should be required. Our survey revealed a divided opinion. The general consensus seemed to be that the cafeteria style involving electives from several categories was not effective, and that it would be better to provide some focus. I know that Rice University is considering a "coherent minor" for all students, in which the liberal arts students must minor in a scientific discipline and all science and engineering students must select a liberal arts minor in which courses from several departments are structured to reinforce each other. This idea could be carried one step further and the courses themselves restructured, rather than using a menu selected from existing offerings.

Structured Options

Even though some room in the curriculum may be provided by the measures discussed, it will probably be too little to provide the range of abilities needed. The second possible action, then, is the use of structured options. Many schools do this already, to a limited extent. The idea is to offer, say, three courses designed to provide some additional expertise in an area such as bioengineering, materials science, polymer science, separations, applied mathematics, electronics, or chemistry. Completing such an option, which might require a slight increase in total hours for that student, should be recognized by designating it on the diploma. Such an action would be intended to increase the marketability of students by increasing their ability to function effectively during their first job, and to make it easier for them to extend their education in these areas after leaving school. This additional qualification may or may not command a premium price, but it should make it easier for the graduates to get jobs.

Improved Use of New Technology

In 1959, I studied chemical process design under the late Bob Perry. Our university had an IBM 650, a marvelous machine with 2,000 words of storage on a rotating drum that used punched cards as input.

The compiler required three passes with cards to produce a machine language program. There was no applications software available at all—if you wanted to solve a bubble-point calculation, then first you had to write a program to do it. Even then, though, the enormous possibilities to aid process design were evident. We used that computer, hands on at night, to improve our understanding of process design. Each time we wrote a program, we would think, "Never again will I have to do that iteration. Never again will I do a tedious, approximate graphical solution to this problem because now an exact solution is no more trouble." It was relatively easy to try different configurations of equipment, as in multiple-column separation systems.

Now it is possible to do "what-if" calculations on whole processes and to even get theoretical, *a priori* estimates of the best possible separation schemes involving all known separation methods. Expert systems programs can be constructed to help guide the novice engineer through the reasoning process that was once the province of experienced consultants. Complex problems in structural analysis, heat transfer, and fluid flow are routinely solved numerically.

In the past 20 years, the evolution in computer technology has done far more than make repetitive calculations faster and more accurate. One can now do things *differently*, not just faster. Talks with new employees and others seem to indicate that the universities are far from exploiting this capability. It is now possible to concentrate on improving the students' judgment, assuming that calculations can and should be made to the accuracy and degree of complexity warranted by the problem and available data. The student can be taught to consider what other data might be needed, assess the cost and time needed to obtain them, and evaluate the probable outcome of experiments. Experimental design and economic analysis can become a routine part of all evaluations, because complicated statistical inference or discounted cash flow analyses become relatively easy to do.

Computers are now a ubiquitous tool. Electronic communication is becoming routine. Word processing, spreadsheet programs, relational data bases, desktop publishing, and computer-aided design are now ordinary tools, just as the slide rule was in the 1950's. The university must teach the student to use these tools effectively—not just to manipulate them but to understand how they can contribute to technical productivity in all ways.

Any hardware that is made commonly available, such as terminal facilities, must be available in sufficient quantity and be well maintained. At many schools the inconvenience to the students of inadequate ways to access required computer equipment is staggering. You know about the kind of graffiti that is started by one student, then added to by another. At one university, the first student posted a sign on the computer-room door with Dante's words marking the gate to hell [4]:

> **Beyond me lies the way into the woeful city.**
> **Beyond me lies the way into eternal woe.**
> **Beyond me lies the way among the lost people.**

to which another student had added, "And beyond *that* lies a three-day wait for a terminal!"

To integrate computer technology into the undergraduate curriculum will require a major commitment of funds and time by the university, the faculty, and the students. But it must be done. Not only should adequate common facilities be provided, but every student should be required to have a relatively powerful personal computer that will run engineering software. All will also need standard commercial software for word processing and the like. These tools will be an inevitable part of the cost of an engineering education.

Forward-Looking Textbooks

Another major point by the Septenary Committee was that texts will have to be rewritten and courses completely revised to implement the first three potential action areas listed in Table 5.

After reading the report, Professor Byron Bird wrote each of the committee members [5], expressing his endorsement of the report and particularly of the recommendation that new textbooks be written. He enclosed a copy of his 1983 article in *Chemical Engineering Education* on the subject [6], and added the following comment:

> **. . . Ch.E. has suffered in the past decade or so because of a noticeable lack of exciting, sparkling, and responsible modern textbooks. Our professors are too busy getting money for research grants and accounting for it, and the sad result is that our most prominent and brilliant researchers and teachers are being actively discouraged from taking time out (for) text-book writing!!**

He went on to make several points about the role of textbooks in a changing chemical engineering field:

- **In a very real sense, good books *bring about* change.**
- **The very boundaries of what we mean by chemical engineering are *determined* to a significant extent by its textbooks.**
- **The field of chemical engineering will inevitably be known and measured by its journals and books.**

Professor Bird's article suggested that "book-writing" ought to be included as a third principal activity of a university teacher, in addition to teaching and research, since it is concerned directly with the production, organization and dissemination of new knowledge. How the writing of forward-looking texts might be encouraged will be discussed later.

More Emphasis on Advanced Degrees

The first four possible actions in Table 5 relate to the undergraduate curriculum and to teaching methods and tools. The last two are concerned with education beyond that.

References to "terminal" masters degrees are often made with a sneer. Why should there be some sort of stigma attached to wanting more than an undergraduate education, but less than a PhD? If we did not all believe that technical knowledge and excellence translate into better job performance, we would not be here. We should encourage students to learn more, even beyond the undergraduate level, before entering industry. I would much rather hire an MS degree holder than a BS, because the percentage of technical courses taken is far higher. Much of the undergraduate program is devoted to humanities and other broadening courses, as it should be, but graduate work is almost exclusively technical.

It is surprising that this trend is not already apparent. Part of the reason it is not may be that many of those responsible for hiring in industry do not realize the impact of curriculum changes during the past 20 years. They have a mental image of those 145-hour BS requirements with virtually no electives common then, rather than the 128-hour programs heavily laced with electives and distributive requirements common now. Also, as enrollments decline, the tendency at some schools is to lighten the workload to keep as many students as possible in the program. These same people who remember the 145-hour curricula also remember being torqued to the breaking point because chemical engineering was *the* premier, prestigious subject to take—those who wanted the label had to be ready to pay the price. Today, the electrical engineering schools are employing the same Draconian measures to reduce enrollment to the dedicated core.

Whether you accept this reasoning or not, you may agree that the natural process in a buyer's market is to be more and more demanding of the quality of the product. I believe that the natural result of this process will be to move toward the MS as the typical final degree in chemical engineering, rather than the BS. There may not be so much of a price premium paid, but the MS recipients will have first call on the available jobs. Remember the earlier point that engineers in the future will do more technical work for a longer period of time than may have been the case in the past.

In the present academic system, where most graduate students are paid, the MS candidate can represent a drain out of proportion to his contribution. This problem causes some schools to discourage MS candidates. However, with a good program there is no reason to have to pay students to attend. Consider, for example, the better business schools. People fight for the privilege of re-entering school at an average age of 25 or 26, to pay $20,000 in tuition and spend two years getting a master's degree. Why? Because the buyers are willing to pay for a premium product. The press is full of articles about how MBA's from the big schools are not as good as they think they are; nevertheless, the firms hiring them are willing to pay a premium of perhaps $10,000 per year for that differential. The number of them getting jobs is also virtually 100%.

Continuing Education

Continual change and the need to adapt are synonymous with continuing, lifelong education (Table 5). A professor once told me that one of the goals of the formal educational process is to prepare students and motivate them to continue their education themselves, without the need for spoon-feeding. That is a laudable goal, but most people either continue to need spoon feeding or retrogress to that stage after a few years of using only a subset of their hard-won skills.

One aspect of emerging technology will have a dramatic effect on continuing education. Videotape combined with teleconferencing and electronic mail is making it possible to extend the classroom over the entire country. Several regional efforts have been successful, such as Stanford University's programs in electronics and electrical engineering. Others are planned. At least one national capability exists, the National Technological University (NTU).

The NTU has leased microwave channels and has become an advanced degree-granting institution. They do no instruction themselves, but rather contract with universities to do it. Although many of the offerings are short courses, it is possible to enroll in a masters degree program in electrical engineering, computer engineering, or manufacturing systems engineering. The students may participate in actual classroom instruction, in real time, by videoconferencing or telephone, or in delayed time by videotape relay. They actually enroll in the university giving the instruction. The professor receives additional compensation through consulting fees, and the university receives a negotiated tuition.

For the student, the courses are expensive (perhaps $1,000 per course) and the company must pay a hefty one-time subscription fee, and set up a microwave receiver, provide a "classroom," and fur-

After reading the report, Professor Byron Bird wrote each of the committee members, expressing his endorsement of the report and particularly the recommendation that new textbooks be written.

nish proctors for examinations. In many cases, however, this arrangement is much cheaper than in-house instruction, and almost infinite variety is possible. It also potentially can provide continuity even though the student may be transferred to a distant or remote location. Because the programs can be recorded, people who travel extensively in their jobs can make up lost work. These latter two issues are major problems to the continuing education of engineers in industry.

This kind of capability has the potential for great change in the way instruction is provided, at any degree level. For example, honors students in high school might begin university courses without the social penalty of leaving their age group. Undergraduates could take complex interdisciplinary programs involving selected courses not available locally. Perhaps most important of all, it could revitalize emphasis on teaching instead of research.

Think about it. You have surely heard comedians on television bemoaning the departure of the Catskill circuit . . . and musicians, the virtual disappearance of the community band. These sources of entertainment fell victim to the ready availability in every home of outstanding entertainment, so that amateur efforts in comparison seemed paltry and inadequate. Now, who do you think will get the extra pay and prestige for national televised instruction? Once people see how much easier it is to learn from truly outstanding, well-prepared teachers who emerge to prominence as teachers rather than researchers, some schools that continue to neglect teaching may find themselves on the educational Catskill circuit.

Another example is instruction in the military. Years ago in the Artillery and Guided Missile School at Fort Sill, Oklahoma, I was amazed to see the amount of technical information that could be imparted to a relatively unsophisticated audience within a few weeks. The secret was preparation. Every lecture was planned, rehearsed, and revised, and no effort was spared to design and prepare audio-visual and mechanical aids to instruction. There is little incentive for this approach in many universities, but there will be when national video participative instruction becomes widely available.

The best defense being a good attack, we should examine this new technology to see how it can be used to advantage in the production of chemical engineers who will be in wide demand in many industries.

LEADERSHIP

The real issue for the chemical engineering profession is leadership—who should provide it? A year or so ago I attended a week-long course in Washington sponsored by the Brookings Institute on "Understanding Federal Government Operations." It featured presentations by many officials, both elected and appointed, from all branches of government. A repeated theme was that the congress views itself as a reactive body. Its members do not believe that their job is to lead, or to anticipate change, but rather to sense the desires of the populace and react—a spiritless point of view, I thought. Doesn't possession of great knowledge and power carry with it an obligation to lead?

There seems to be a reluctance on the part of the academic community to lead change in the profession of chemical engineering, as well as a reactionary force to resist change. There are no doubt many contributing factors. For example, some of the better schools still find themselves to be in a seller's market; their graduates are easily placed, partly because they can still impose high selectivity on incoming talent. They also have the financial flexibility to enter any new field with additional faculty and facilities, so that change occurs through a comfortable growth process without the necessity for major sacrifices. In a shrinking field, though, those options are not open to most.

As an example of reactionary influences, consider one of the barriers that Professor Bird cited concerning writing texts. Neither young professors on the tenure track nor active researchers needing a continuing series of research publications believe that they can afford to take the time to write books.

Each school will have to address most of the foregoing issues, taking into account its own financial and personnel resources, state regulations, and the like. The ASEE and AIChE have a stake in the outcome and should consider how some degree of national coordination might be achieved. There is one important issue, though, that might benefit from active involvement of industry and government, as well as the academic community, and that is to encourage the preparation of outstanding textbooks.

Providing Forward-Looking Textbooks

As a student of Jack Powers at the University of Oklahoma in 1959, I was one of the first undergraduate guinea pigs for the "Notes on Transport Phenomena." That volume was John Wiley and Sons' preliminary edition of Bird, Stewart and Lightfoot's famous book that accomplished for that period of time all of the things for the field of chemical engineering that Professor Bird urges others to do today. The field of chemical engineering underwent a dramatic change between 1955 and 1965, and their book was a powerful force for that change.

Bird cited two other quotes:

> **The true University . . . is a collection of books.**
> ***—Carlyle***

> **There must be more books, for engineering data and interpretation of results are fundamental needs.**
> ***—Chilton***

But Bird's point about textbooks "determining the boundaries of the field" may mean either to expand or to circumscribe them. Unfortunately, because of the pressures disfavoring time spent in pursuit of writing books, many are far from revolutionary. As Robert Burton said in the early 17th century, "they lard their lean books with the fat of others' works" [7].

Some of the disincentives to writing texts are that the task

- **Is time consuming.**
- **Distracts from portions of the job considered critical to professional success—research and funding.**
- **Is not financially rewarding.**

These items would have to be addressed just to generate more books. But what is needed is not merely more books, but novel and different ones, written with a coherent goal to allow compaction of the curriculum through sharper focus—books that will use the new tools of today to impart information needed for tomorrow.

The Septenary Committee recommended that the content of every course in the chemical engineering curriculum be examined and changed where necessary to meet a number of criteria and urged that textbooks be rewritten in major ways. But how can incentives be furnished, and who will provide the needed focus over several years?

TABLE 7
Leadership

- **PROFESSIONAL SOCIETIES SHOULD LEAD**
- **SUPPORT SHOULD EMERGE FROM**
  - **— Government**
  - **— Industry**
  - **— Universities**
  - **— Publishers**
  - **— Authors**
- **FUNCTIONS OF LEADERSHIP**
  - **— Establish Goals**
  - **— Focus Activities**
  - **— Communicate**
  - **— Remove Obstacles**
  - **— Provide Incentives**

Leadership to change the field through improved texts is not likely to emerge spontaneously from the academic community, nor to spring from present market forces acting upon prospective authors. The remaining possibilities would seem to be government, industry, publishers, and professional societies. How might all six groups combine their efforts toward improving the supply of well-prepared chemical engineers, capable of contributing to the needs of government and industry in a way that rewards the authors and their employers appropriately to the degree of effort and accomplishment involved.

Once people see how much easier it is to learn from truly outstanding, well-prepared teachers who emerge to prominence as teachers rather than researchers, some schools that continue to neglect teaching may find themselves on the educational Catskill circuit.

Let us suppose that the goal is to persuade young, active research professors, already tenured, to devote the effort and time needed to write really good textbooks in chemical engineering. Furthermore, we want these books to incorporate examples in the newest technologies and to build computer applications into their core. If possible, we should like to encourage co-authorship, preferably by those representing more than one academic discipline or by a blend of perspectives from industry and academia.

As stated in the first item of Table 7, leadership should be provided by the societies, whose stake is in the preservation and enhancement of the profession. The Chemical Engineering Division of the ASEE, the AIChE, and the Chemical Research Council are examples of organizations whose fortunes rise and fall with that of the profession itself. There are, of course, other possibilities. For example, the "National Electrical Engineering Department Heads Association," which I am told has received NSF funding, meets annually to discuss issues important to that group.

Let us assume for a moment that some society would take on the role of setting goals, defining requirements for a series of texts that would achieve these goals, and reviewing the competing proposals that would be submitted if suitable incentives were provided. The society could establish a prize, say \$100,000, split one-third upon selection of the winning prospectus and two-thirds upon acceptance of the final text by the society's reviewing committee and a publisher.

Financial support could come from both government and industry, and the universities could contribute faculty-release time for course preparation and text review as well as sabbatical leaves. A number of universities might agree to help evaluate draft texts and use the new texts for at least a trial period.

The next essential element is the publisher, who might agree to establish a series for these books and provide a standard set of rewards for the authors, over and above the initial prize.

The final element is the author. Another Robert Burton remark [8], is that philosophers advise you to spurn glory, yet they will put their names to their books. Prestige is a powerful motivating force, but this plan would allow the author to gain not only in reputation as an author and prizewinner but also to minimize the financial penalty.

Who would gain? Everybody. These thoughts have been discussed with a number of people in industry and academia. Most agree that money spent on stimulating the writing of really good textbooks would do more than an equivalent amount of money spent directly in support of research.

SUMMARY

When the future of chemical engineering is the subject, there is indeed much to talk about. First, some of the signs of change facing the chemical engineering profession were described and the underlying reasons for them were proposed.

Next, you were urged, as members of the academic community, to adopt a market-oriented attitude in addressing the needs of your traditional customers, the industries who have long employed chemical engineers. But also you were encouraged to include the electronics, food, health-care, aerospace, and other industries whose need for chemical engineers might be expected to grow in an increasingly technological society oriented toward high-value-in-use specialty products.

We then reviewed six areas of action to address the needs of industry by expanding the capabilities and improving the training of chemical engineers.

Finally, the problem of leadership was raised and the need for cooperative action in several areas was stressed. A way was suggested by which your society or other professional groups might enlist the aid of industry and government, as well as focus and coordinate your own efforts, to define goals and stimulate the creation of outstanding texts. Cohesive leadership must form the cornerstone of any effort directed toward stimulating evolution in the field of chemical engineering.

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