CEE chemical engineering education
VOLUME 2 · NUMBER 1 · WINTER 1968

CHEMICAL ENGINEERING DIVISION OF AMERICAN SOCIETY FOR ENGINEERING EDUCATION

BIRD-on wisconsin
KELLER-mass transport in human circulatory system
STEVENS-dynamic optimization
WISSLER-transport phenomena lab

also
Aris
Canjar & Manning
Levenspiel
Tomkowit

featuring this issue
JOE KOFFOLT of OHIO STATE

Chemical Engineering Education

VOLUME 2 NUMBER 1 **WINTER 1968**

Departments

Feature Articles

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EDITORIAL

Editorializing, philosophizing, polemicizing, exorcizing, "exhortizing," proselytizing, prophesizing, and all similar conventional activities of an editor must wait for future issues. In this issue, nothing is more important than saying "Thank You" to the many people who have contributed time and money to the publication of **CHEMICAL ENGINEERING EDUCATION.** These are:

Professor William Corcoran of California Institute of Technology, for his leadership as Chairman of the Publications Board and his diligence in obtaining financial support from numerous companies.

The other members of the Publications Board for their support and for serving as our geographical advertising representatives in securing donations and ads from industry. Their names are listed on the first page.

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The companies that have generously contributed to our support (see acknowledgments).

The Chemical Engineering Departments that have donated $25.00 each to the journal (see acknowledgments).

The former editorial staff at the University of Rochester who have helped make the transition smooth and have offered their advice and support, and especially Professor Shelby Miller for his dedicated efforts in publishing Volume 1.

The Publications Staff at the University of Florida, College of Engineering: Rachel Albertson, Sandra McFarlan, Ginger Ashley.

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The staff at the University of Florida, and especially Professor Mack Tyner and Professor R. B. Bennett.

The authors of articles who have cooperated by supplying us with material requested of them.

Our many "well wishers" throughout the country.

CHEMICAL ENGINEERING EDUCATION will continue to need the support of all these people and of others if it is to thrive or even to survive. The editors would especially like to urge all of you to submit material to us for our recurring departments:

Course outlines (no discussion needed)

Home problems, exam problems, and questions of interest.

Views and opinions of general interest, including guest editorials

Course descriptions and discussion

Book reviews (both before and **after** use)

News of conferences, new appointments, changes in programs, etc.

New laboratory techniques

Your department of chemical engineering (see "On Wisconsin")

An outstanding chemical engineering educator (see "Joe and his Jewels")

As a requirement of NSF sponsorship, we have agreed to publish the proceedings of the

Continued on page 39.

Each issue, we will feature a department of chemical engineering. We begin with a top-rated department that has produced numerous outstanding chemical engineering educators and scholars.

ON WISCONSIN

R. BYRON BIRD, *Chairman*

For many years the Chemical Engineering faculty at the University of Wisconsin has been split into three factions: the canoeists, the golfers, and those who steadfastly refuse to join either of the other groups. On most academic and administrative matters we usually have N + 2 opinions, when N is the number of professors (the extra "2" arises from the fact that several professors usually change viewpoints along the way). Because of this lively lack of unanimity it is sometimes remarkable that we can ever get our vectors lined up with a resultant component in the direction of progress. When we do, however, we are fairly confident that the concensus is workable. In what follows I shall attempt to outline very briefly our conclusions on a number of points related to chemical engineering teaching. Many of these reflect the strong leadership our department has had in the recent past, particularly that of Professors Hougen, Ragatz, and Marshall.

Research is teaching

There has been far too much talk about research VERSUS teaching. We feel strongly that research is a vital departmental activity and that the individual and small-group instructions involved in research is one of our important *teaching* activities. It also serves to keep the teacher alert by insuring that he is faced daily with new problems to which he does not know the answers, that he is required periodically to present and defend his ideas at technical meetings, and that he is obliged to know what is going on in his area of research in industry and other academic institutions. The teacher thus, in a sense, continually puts himself in the role of a student and thus can appreciate the problems that his own students have when they encounter a new situation. Nothing is more oppressive in an educational institution than a teacher who presides over a body of stagnant knowledge and demands that his students master the material obediently.

The flow of knowledge

It has generally been our policy that each undergraduate course is backed up by a graduate course, and that it in turn is backed up by a research program. In this way there is a continual flow of knowledge from the research laboratory into the graduate course; often the person doing the research also teaches the graduate course and he is then free to experiment on new ways to organize and teach the material. Once the material has been class-tested at the graduate level it can be moved down into the undergraduate program. The several undergraduate textbooks prepared in our department have been developed by this kind of procedure.

Attitude of "apartheid"

Our department has for many years gone on the record as being opposed to the "common core" idea in engineering education. We feel that such regimentation can possibly lead to a lack of flexibility and a lack of identity. Also, the strong chemistry background of our students is not made use of if they take common core courses in thermodynamics, fluid dynamics, materials science, etc. Furthermore, it seems to us that students should learn early in life the importance of making a decision and accepting the consequences. If a student makes the wrong curriculum selection and has to change his course of study, it may be that he will have profited from the experience in decision-making. Finally we feel that it is good for the students to identify themselves with an academic department early, for the purpose of developing *esprit-de-corps* and for advising purposes. This is particularly important in a large university. Our attitude of maintaining in-

Our attitude of maintaining independence from the rest of engineering should not be interpreted as an indication of disrespect or non-cooperation, but rather as a professed desire to be the connecting link between chemistry and engineering.

Professor Roland Ragatz, former chairman, and Professor R. B. Bird, present chairman, Department of Chemical Engineering, University of Wisconsin.

dependence from the rest of engineering should not be interpreted as an indication of disrespect or non-cooperation, but rather as a professed desire to be the connecting link between chemistry and engineering.

Importance of chemistry

The distinguishing feature of chemical engineering, as opposed to other engineering, is the strong emphasis on *chemistry*. We have maintained a substantial chemistry sequence in our curriculum, and our students are in the same courses as chemistry majors. We have not eliminated analytical chemistry, because we feel that the interface between analytical chemistry and process control is an important one for future development. We have tried to keep a strong chemical bias in all of our chemical engineering courses, emphasizing wherever possible those problems dealing with mixtures, chemical reactions, multiphase systems, molecular structure, polymers, interesting compounds, chemical separations, and ionic solutions. We are trying to make a conscious effort to stop talking about the famous compounds "A" and "B" and use examples involving real chemical systems. Our last six professional staff additions have been purposely made in such a way as to strengthen the chemical orientation of our department. We are not trying to imitate chemists nor are we trying to become totally dependent on chemistry as a source of inspiration and guidance; but we must not be oblivious to the great advances in chemistry in the last two decades (the *Westheimer Report*, an enlightening, easy-reading summary of the advances in chemistry since 1946, ought to be required reading for all ChE professors over 40).

Engineering emphasis

There seems to be misunderstanding in some quarters about the engineering orientation of our undergraduate curriculum. The publicity associated with the development of our transport phenomena course seems to have misled some people into thinking that we have abandoned all reason. We regard the transport phenomena course as a third semester of physics, made necessary by the fact that elementary physics includes almost no material on fluid dynamics, heat conduction, and diffusion. We still include in our curriculum two 3-credit lecture courses in unit operations, a 5-credit unit operations laboratory course, as well as courses in chemical reactor operation, process dynamics, and process design. In all of these courses the emphasis is very much on solving problems of engineering interest. The laboratory instruction in chemical engineering includes: transport phenomena, unit operations, applied electrochemistry, process control, and polymer processing; all of these except polymer processing are required. This laboratory instruction is quite substantial and we feel that this is essential in maintaining an engineering emphasis.

Importance of undergraduate instruction

Our department pays more than just lip service to the undergraduate instructional program. Almost every staff member participates actively in undergraduate teaching and advising. With an

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undergraduate enrollment of about 350, we have to devote a substantial part of our effort to course planning, instructional equipment, course notes, supervision of teaching assistants, and lecture preparation. We are also trying more and more to assign extra time when needed for course improvement. All undergraduate courses are given each semester, and enrollments in some courses are as high as 50 to 80. We have experimented with large lectures, small sections, and various "intermediate forms of instruction. We have found supervised problem-working sessions to be of value in some courses: in these, a portion of the homework is done under the guidance of a teaching assistant who circulates around the room and gives advice where needed. We have one standard curriculum for all students. However, those with a grade-point average of 3.5/4.0 may elect to replace any 6 credits of chemical engineering courses by 6 credits of any science or engineering courses. We do use quite a few teaching assistants (about 24 to 30 quarter-time graduate students) mostly for taking care of laboratories, problems sessions, and paper grading; occasionally they are given major lecturing assignments as well.

Graduate courses

Most of our graduate courses have a strong science and research flavor. They are intended to be of interest primarily to the Ph.D. candidate, who is preparing himself for research. We have never developed a strong terminal MS program at Wisconsin and very few of our courses are suitable for those not seeking the doctorate. The number of graduate courses we offer is purposely kept rather small. We want the few courses we do offer to be well-organized and up-to-date. We encourage our students to take courses in the basic sciences or other engineering departments so as to bring new ideas into chemical engineering. We have no course requirements in chemical engineering for the Ph.D. We have quite a few small seminars in the department and auditing of courses is widespread. In summary, we oppose formal course proliferating in engineering at the graduate level.

Graduate examination procedures

Prior to the final thesis examination, we have three formal graduate examinations in chemical engineering. The *MS examination* can be an examination on an MS thesis. Otherwise it is devoted to the critical presentation of a recent article in one of four chemical engineering journals. This type of an examination hopefully encourages some familiarity with the technical literature and also helps to bring new work to the attention of the staff. Rather than being a teacher-*vs.*-student exam, it is more teacher + student *vs.* someone else's research. The *qualifying examinations* (beginning of third semester) are four 4-hour tests on basic undergraduate material: transport phenomena, thermodynamics, process dynamics, and chemical reactors and kinetics. These are intended to insure that we are not turning out students with poor foundations covered with a thin veneer of high-powered, science-oriented graduate material. The *preliminary examination* (beginning of fourth semester) consists of a report, about 100-200 pages, on specific plans for the Ph.D. thesis research, including basic theory, literature survey, detailed equipment plans, estimated costs, and time schedule. The purpose is to insure that the candidate has research potential and that the problem is realistic and of finite duration. I think most of us also feel that it is to some extent an examination of the major professor. Often some very good ideas come out of the two-hour oral presentation of the report.

Foreign language requirements

At Wisconsin the language requirements are left pretty much up to the individual departments. We currently require either the traditional minimal reading requirement in two languages or else advanced competence in one. We allow any languages to be used, recognizing that some want the competence as a research tool, whereas some may wish to train themselves for an overseas assignment. Still others may wish to capitalize on a foreign language spoken at home in their youth. There seem to be two major problems at the present. One is that the language departments have gone over to machine-graded tests which we suspect do not encourage the right motivation for language study. The second problem is that most undergraduate engineering curricula do not require foreign language study. We have recently made one change in our curriculum aimed at encouraging foreign language training: we allow students who have had two or more years of a foreign language in high school to continue that language during their freshman year in lieu of freshman English.

Professional staff

We believe that it is in the best interests of the students to provide for them a staff with widely varying backgrounds (in addition to golf *vs.* canoeing). For example, as regards the industrial experience of our professors we have a spectrum going from 0 years up to 15 years. We have some who specialize in research, others who specialize in teaching. We have some with strong ties to chemistry, but others with strong ties to electrical engineering, biomedical sciences, metallurgy, mechanics, etc. About 4/5 of the staff have Ph.D.'s (or Sc.D.'s) in chemical engineering, but 1/5 got their doctorates in chemistry or polymer science; we feel that having about 20 percent to 25 percent of the staff with their doctoral training in a related field can bring in many new ideas and viewpoints. But the one thing we require of all of our staff members is independence. We do our best to hire new professors in fields not already covered by the present staff so that the newcomer will develop his own niche. We want our students to have a diverse group of experts available to them as consultants.

The above items we seem to have reached agreement on. But, like all departments, we have a number of controversial problems as yet unsolved. One perennial problem is that of *report-writing*; everyone (students, T.A.'s, professors, and employers) agrees that there is a serious problem here and numerous remedies have been applied. Part of the blame possibly rests with the high schools, but much of it is doubtless a result of the unfavorable student-to-teacher ratio; expert writing is a result of long, careful tutelage, and I doubt that it can be mass-produced.

Another problem is that of *graduate-student support.* All departments face the annual job of matching fellowships with students. Inequities seem to be inevitable because of allowances for dependents, income tax regulations, tuition refunds, eligibility for supplementation, etc. About the only point we seem to agree on in our department is that no supplementation (aside from quarter-time teaching for NSF fellows) will be allowed for first year graduate students. We do not believe that supplementation, travel expenses, or other enticements should be part of the graduate recruitment activity. Students should select their graduate school on the basis of the program and the facilities.

Another problem is that of *postdoctoral research.* We get many letters from persons seeking postdoctoral appointments. We have to turn most of these down for lack of funding. In many instances the persons would do better to get industrial experience, but many of the requests are legitimate. A postdoctoral year is valuable for persons switching from industry to teaching, or from one teaching position to another. Postdoctoral research during a sabbatical year can be quite stimulating. Postdoctoral research in a department can often be used to spearhead a new area or to provide an extra push in a graduate research program. We certainly have not discussed this matter enough.

Of continual concern are the *potential new areas* of chemical engineering. I doubt if we do enough experimentation and exploration in trying to bring in new subject material and techniques into chemical engineering. We have been far too slow in emphasizing colloidal phenomena, polymer processing, catalysis, multiphase systems, and other subjects whose importance seems to be well recognized in industry. We probably do not spend enough time on this at the departmental level.

Needless to say the problem which concerns most of us is *time.* One wonders whether the leisure days in the ivy-covered halls ever really existed. The faculty member today has enormous demands put on his time: research, teaching, proposal-writing, continuing-education programs, industrial consulting, attendance at meetings, reviewing of research proposals, etc. We must in the near future seek new ways of insuring that staff time is being effectively utilized. Finally there should be enough time left over for the canoeists to convert the golfers, or to discuss the relative merits of making popcorn by transport phenomena methods or by the unit operations approach.

In this issue, our featured chemical engineering educator is Professor Joe Koffolt, chairman of the Department of Chemical Engineering at Ohio State University, who writes fifty letters a month to his former students—"his jewels." This article was submitted to us by Professor Aldrich Syverson of Ohio State University, Columbus, Ohio.

JOE and his JEWELS

Dr. Joseph H. Koffolt is entering his 39th year of teaching chemical engineering at Ohio State University, Columbus, Ohio. "There is no similarity between what we taught ten years ago and today," notes Koffolt, chairman of the department since 1948.

Chemical engineering began at Ohio State in 1902, the same year Koffolt was born in Cleveland. In 1924 he received the department's 310th chemical engineering degree and next year he will hand out degree number 2700. Koffolt's teaching career spans more than half the time his subject has existed.

Chemical engineering, he says, evolved from industrial chemists who were good pipe fitters and plumbers.

Koffolt, smiling, recalls "putting on long pants and lying about my age" when, at 14, he went to work for Union Carbide as a block grinder. "Nine cents an hour, ten hours a day—it was just a summer job, but Dad thought I was doing pretty good," grins Koffolt through a haze of Ibold cigar smoke.

Things had improved a bit by June, 1924, when Koffolt got his first job after graduation. He worked for Industrial Rayon Corporation in Cleveland. His starting pay was 43 cents an hour, "with a chance to work up to 45 cents." When he started, experienced sniffers and tasters were responsible for solution strengths. He adapted nomographic (alignment) charts to the business so that if a man could read, he could run the process.

By making what he calls "relatively simple" changes in equipment he was able to increase production from 250 to 5,000 pounds of rayon per day, with no increase in men. "I did quite a bit of good there," he muses. Koffolt still uses some of his notes, "disguised and dummied up," to pose problems for students.

Koffolt, author of a book on "application" of chemical engineering, has a long list of papers to his credit. Among his consulting activities have been fire and explosion investigations. Asked what the usual causes for these were, he replied "damn fools who are supposed to be experts."

Highlight of his professional activities is his term as vice chairman of the membership committee of the American Institute of Chemical Engineers. When he took office, only about 150 men ("the majority of them from Ohio State") belonged. By the end of his term he had boosted membership to about 3,000, a feat which netted him the society's "founder's award" in 1963. "Why, that group was so poorly publicized that when I was in school I thought it was a secret society and you had to know the password," he recalls.

Koffolt has belonged to the American Society for Engineering Education since 1933 and, in the chemical engineering division, has held every office but one.

Koffolt's office walls are lined with pictures of his former students. He also has a small mineral collection close to his desk. Both are important to him.

Of the alumni, he says: "Here—these men, the graduates—are the real highlight of it all." And, of his minerals, he says: "I like rocks, only we call them minerals. Look here, and here, see how each one has different characteristics, is shaped differently and intricately? I think, looking at these rocks, that God must have had a lot of fun when He created the world."

Koffolt is willing, even anxious to talk about his alumni and their accomplishments. I believe we have the strongest alumni group in the country," he declares. "They're a close-knit, enthusiastic group."

"Our support from industry is amazing," he boasts, naming donations like chemicals, laboratory equipment, money, a computer, and sometimes even borrowed brainpower. Laboratory fees, he declares with pride, are the same as they were in 1924.

Since 1958, Koffolt has secured for his department more than $300,000 in contributions and is credited with "getting" the modern chemical engineering building. Since he has been chairman of the department, he has also written and sent an "annual report," sometimes over 30 pages long, to his alumni.

How is it that Koffolt is so successful getting money from his alumni; how does he know so much about them, keep in touch so well? For Kofolt, the answer is simple. "I decided when I started to teach that I owed an obligation to the children of the state. I was going to know everybody I taught and not forget them."

And, though he may not remember every one, he cheerfully talks at length of his alumni. Like Cornelia, he refers to them as his "jewels." Obviously enjoying himself, Koffolt points to a a picture on his wall and says "There's Bob Bates; he founded Chemineer, and sometimes when he consults he recommends his competitor's equipment. And Harry Warner, president of B. F. Goodrich. Parker Dunn—he was in my first graduating class—is president of American Potash. Dale Barker there is head of *Chemical Abstracts*, and Herb Barnebey is president of Barnebey-Cheney, an activated carbon manufacturer.

"Cy Porthouse is president of Dunhill. He's contributed over $20,000 to the department, and he once raised two million dollars in two days. His father was a bricklayer. Edgar C. Bain is retired, but he became vice president for research of U. S. Steel and has a research laboratory named after him. I remember one graduate who just made it with a 2.01 grade average and no one thought he would go far. But he had a lot of common sense and a good feel for things and now he's manager of one of the world's largest chemical plants."

Koffolt's alumni are generous. One man, responding to a money request, came to his office, called him a "pipsqueak," and gave him $10,000 worth of stock. Another, in his will, left the department $75,000.

Koffolt writes about fifty letters a month to his jewels. Grinning, he points to a dictaphone and says "that thing is a godsend." He sends 700 Christmas cards, and can recall when he wrote personal notes on each one. "I can't do that anymore," he sighs.

Asked why he was made chairman of his department, he chuckles and replies, "Because I knew all the rules." Seriously, he says he accepted because he wanted to increase alumni ties, which he calls "our most important asset." He also wanted to improve teacher retention, and is proud of only two resignations in almost twenty years. And he has distributed the teaching load better. He recalls that before he was made chairman, he had more than forty graduate students. This, he felt, was "very wrong . . . very unfair to the students."

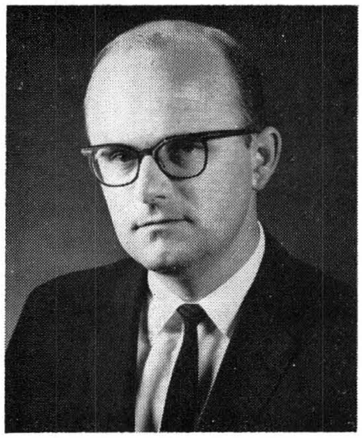
"When I was made chairman," he continues, "I decided that every one I hired had to be smarter than I was."

On peeves, Koffolt barks "Too damn many forms." And his greatest failing? "I talk too much." Asked about hobbies, he replies "Really, my hobby is people. I like them. Every person is different, and they're all good."

Koffolt claims his greatest accomplishment is his relationship with his jewels. His alumni are located in most states, and in some forty countries around the world. He brags: "I can go about anywhere and call an alumni meeting." He is also

CHEMICAL ENGINEERING DIVISION ACTIVITIES

L. BRYCE ANDERSEN, Chairman



The Chemical Engineering Division of ASEE serves the interests of chemical engineering faculty and others concerned with the education of chemical engineers. In this period of intense reexamination of GOALS and goals, the Division serves as a liaison with other engineering fields within ASEE. In all of its activities, the Division tries to coordinate its efforts with the education committees of AIChE.

After a stimulating and well-attended Summer School for Chemical Engineering Teachers held in June at Michigan State, the Division has begun planning for the next Summer School to be held about five years from now. Suggestions on topics, format, and location are welcome.

The Division sponsors a full program on chemical engineering education at each annual meeting of ASEE. Next June in Los Angeles, there will be sessions on "Frontiers in Chemical Engineering" and "New Approaches to Teaching Chemical Engineering." In addition, there will be the annual Distinguished Lecture, a department chairmen's meeting, a luncheon, and a banquet.

In order to serve a broader segment of chemical engineering faculty, the Division has begun sponsoring sessions at AIChE annual meetings. A symposium on Case Problems was presented at the New York meeting, and another session is planned for the Washington meeting in 1969.

Potentially one of the most important functions of the Division is its sponsoring the journal, *Chemical Engineering Education.* After several years of considerable effort by many people, the journal is now established on a sound financial and editorial basis. It should serve as an effective means of communication among chemical engineering faculty.

Continued from page 9.

proud of the 75 chemical engineering professors his department has produced.

What makes Koffolt angry? "These damnfool sign carriers with the big beards," he exclaims, adding "also professors, who are supposed to be professional people, who won't cross a protest line. This makes me mad." Of war he observes that, "We'll never do away with greed. There is free will. There will always be jackasses."

Koffolt is candid, though optimistic, about the future of chemical engineering. "We don't know what's going to happen. Materials are selling now that were unknown a decade ago. We haven't discovered everything yet," he smiles. The future looks bright, he thinks, "but not smooth."

Petrochemicals, the computer, and synthetics are "exciting" things in chemical engineering for Koffolt. Petrochemicals are important because, he predicts, "This is the way we're going to lick the food problem." Koffolt, criticizing chemical engineering somewhat, notes sadly that "It is still about half art, half science." He would prefer that science outweigh art.

"Quite often we don't know what's happening," he admits. "Thirty years ago no one thought of using rayon in tires. And the first pair of rayon panties—when they were washed and hung out to dry, they stretched out to about two feet."

Asked for a funny story, for which he is noted, Koffolt bowed out gracefully, quipping "My stories come like a Quaker talk—when the spirit moves me."

Why do chemical engineering alumni offer such strong support to the department, Ohio State, and Koffolt? Perhaps it is because, as one jewel wrote in a letter to Koffolt, "if it hadn't been for you and the department, I would probably have been a pants-presser like my father all my life." To this, Koffolt adds "I think they appreciate the interest we take in them."

How do Koffolt's jewels view him? "As Joe."

How does he view his alumni? "Like second sons."

(Use of Programmed Learning Material).

Common Thermodynamics Course

For Engineering Sophomores*

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A macroscopic-oriented course in classical thermodynamics for all second-semester engineering sophomores at Carnegie Tech is described. There was good agreement on course content; however mechanical engineers tended to emphasize availability and irreversibility, while chemical engineers desired increased coverage of property estimation and reduced correlations. Chemical engineers preferred comparatively lengthy problems which closely reflect industrial practice and thus include engineering facts of life as well as basic principles. Other faculty recommended shorter, more mathematical problems which often isolate and illustrate a single basic concept.

Lectures in introductory concepts, work, and temperature were replaced by programmed material with approximately 20 percent saving of time. Student reception was good and their depth of understanding compared favorably with that taught by conventional means.

INTRODUCTION

An introductory thermodynamic course common to all second-semester engineering sophomores at Carnegie Tech was initiated in 1965. The primary objective was to present the student with as broad and general approach as possible instead of the more conventional "denominational" methods which all too often are confined to a particular branch of engineering. Over 200 students attend this one-semester, three-hour-a-week course and in 1965, 1966, and 1967 these sophomores have been divided into: an honors section of 30; a large section of 90; and three or four additional sections of 30. In addition, one or two evening-school sections of 20 are handled concurrently. The course is administered by a Course Chairman appointed by the Dean of Engineering and Science. Each section is taught by a single instructor who handles all student contact for his section. All involved faculty—typically 2 chemical, 1 civil, 2 mechanical, and 1 metallurgy—meet at least once a week for about one hour. It is at these weekly sessions that all decisions on course content, home problems, tests, grades, etc., are reached.

COURSE CONTENT

Two years before this common course was initiated the course content was discussed extensively. In general there was surprisingly close agreement on content. To satisfy the common requirements of the Chemical, Civil, Electrical, Mechanical, and Metallurgy Departments, a traditional macroscopic-oriented approach was selected, thus de-emphasizing information theory and statistical aspects.

Although this general approach has remained fixed, course content has been discussed frequently by the committee of involved faculty. At the start of each year, the Course Chairman proposes a general outline of topics with suggested times. This outline was never "rubber-stamped" by the committee; on the contrary, it was always criticized in detail and modified. In general, mechanical engineers argued for greater emphasis on the concepts of availability, irreversibility and dissipation, while chemical engineers desired more coverage for heat effects and reaction, estimation of properties, and reduced correlations. Eventu-

*Presented at the Annual Meeting of ASEE, June 19-22, 1967.

ally a satisfactory compromise was reached and Table I presents the final version of the 1967 outline.

As soon as all faculty have been assigned to this common course, the Course Chairman calls a committee meeting to assign class sections to the individual faculty and to select a text. The latter problem always presented difficulties and three different texts have been used in three years. In 1965 Sears's text[1] was used. This book was selected because:

1. It represented a general approach and was not "denominational."
2. It presented a classical, macroscopic viewpoint.
3. It was readily adaptable to a one-semester course.

Sears's text suffered from three drawbacks:

1. Engineering aspects were not emphasized.
2. Students experienced great difficulty in converting from the metric system of units to the engineering system.
3. No thermodynamic property data were included.

TABLE I
General Outline of Topics

E 12 THERMODYNAMICS SPRING 1967

Tentative Schedule

No. Weeks	Topics
1	Introduction, Temperature, and Thermometry
2	Thermo Properties, and Work
	1st Hour Test
5	Heat, First Law and Consequences U, H, C_p, C_v; isothermal and adiabatic processes; energy equation for steady-state flow; change of phase, P-T, P-V, ln P-H diagrams; heat of reaction
	2nd Hour Test
4	Second Law and Entropy efficiencies of reversible engines absolute temperature Clausius inequality T as an integrating factor principle of increase in entropy
	3rd Hour Test
4	Combined First and Second Laws availability and irreversibility Maxwell relations computation of properties law of corresponding states reduced property charts
	Make-up Test
	Final Examination

The lack of thermodynamic data was compensated for, at least partially, by handout material much of which has now been published.[2]

In 1966 the committee adopted an engineering text by Van Wylen and Sonntag.[3] This text provided sufficient coverage of all fundamentals and applications but students complained that some topics were covered at great length and this made the text difficult to read. Accordingly, in 1967 another engineering text by Zemansky and Van Ness[4] was used. This book was supplemented by the student edition of Canjar and Manning's data book.[2] Zemansky and Van Ness proved to be easily read by the students but the coverage of some topics was a little scanty.

COURSE ADMINISTRATION

A major undertaking for the Course Chairman is to ensure that the different sections of this common course are kept reasonably together while permitting individual faculty a satisfactory degree of autonomy. This was accomplished as follows. The Course Chairman proposed a detailed outline for each major section of the course (as listed in Table I). As is shown in Table II, the coverage of "First Law" is described by:

1. referring to appropriate passages in several outstanding texts,
2. enumerating the highlights,
3. listing the topics for the homework problems.

These detailed outlines received the same careful discussion and modification as did the general outline. Faculty autonomy was realized because the individual members prepared their lectures independently and no effort was made to influence their method of presentation. Of course whenever "rookie" faculty requested advice on student reaction to previous years' approaches, the "veterans" were only too pleased to cooperate.

The individual sections are kept together by assigning common homework problems at least 90 percent of the time and by giving common tests. This framework compels the instructor to follow the accepted schedule of topics reasonably closely.

The character of any course is determined by the nature of the assigned homework, and this common course derives its uniqueness from the philosophy of its problems. In fact it is this topic which has ignited the lengthiest and most fervent debates. Two philosophies exist. Many instructors recommend a relatively short type of problem

TABLE II.
Detailed Outline of One Topic

E 12 THERMODYNAMICS — SPRING 1967

Suggested Course Content

First Law and Consequences — February 22-March 24

(a) **Suggested Student Reading**

Text	First Law, Batch	Steady-State Flow	Pure Substance Properties
Zemansky and Van Ness	p. 63-87	p. 235-250	p. 194-224
Van Wylen and Sonntag	p. 80-92 honors	p. 250-352	p. 48- 54
Keenan	p. 8-14 19-20	p. 34- 40	p. 44- 57
Smith and van Ness		p. 34-40	p. 118-122 137-143

(b) **Suggested Topics**

1. Define heat, First Law in terms of Joule's experiments
2. Internal Energy, enthalpy, and specific heats
3. Isothermal and adiabatic processes
4. Energy equation for steady-state flow
5. Change of Phase, P-T, P-V, ln P-H diagrams
6. Heats of Reaction

(c) **Problem Topics**

Heat exchanger
Nozzles
Refrigeration
Power cycle
Fuel or electrolytic cell
Battery
Solar cell

in which basic principles are isolated and illustrated. This "theoretical" type of problem is frequently characterized by:

1. It illustrates some single principle and/or equation.
2. A major portion consists of a mathematical exercise.
3. Simplifications are made with little regard for actual practice.
4. All required data are usually supplied.

An example is: "Compute the entropy change of the universe when m gm of water as T_1 is adiabatically mixed with m gm water at T_2. Show that this entropy change is positive."

The second "practical" type problem is designed to acquaint the student with engineering facts of life as well as illustrate basic principles. This type of problem is often:

1. Based on an actual industrial process.
2. Is comparatively lengthy in that it usually involves the interaction of several steps such as compression, condensation, throttling, etc.,
3. Required data may not be provided.

There is not enough lecture time in this course to permit detailed descriptions of batteries, fuel cells, power and refrigeration cycles, etc., so when these devices are incorporated into this type of problem the student is advised to read recommended passages in prescribed texts. This practical type is thus the complete antithesis of the five-minute, hypothetical type which frequently involves the reversible expansion of an ideal gas in a cylinder fitted with a frictionless piston. Because these practical problems are used as an introduction to engineering technology, every effort is made to select numerical values that closely reflect actual practice. These problems are prepared as follows: a faculty member elects a topic, develops a problem, presents it to the committee where it is discussed, modified, accepted or rejected. If accepted, he provides fellow members with a solution—and this solution is not immune to criticism!

A notorious example of the practical problem has been lurking in the Department of Chemical Engineering for about 20 years, and was first used by Dr. Robert York. This problem involves the proposed use of biphenyl in a power cycle (see Table III). The solution requires construction of the required T-S diagram using only scanty specific heat and vapor pressure data. Students must be given at least one week, and should be encouraged to ask probing questions in class before the problem is due. Now students can outline solution methods, identify missing links, etc., before pushing the slide rule. Without such interaction, this problem is too difficult for many sophomores—few will remember that the Clausius-Clapeyron equation can yield the missing latent heats even though it has been mentioned in the lectures. The instructor must provide enough help but should not "give away" the problem.

As a compromise, students are given both

TABLE III
Biphenyl Problem

In order to make a power cycle as efficient as possible in a thermodynamic sense, a double cycle is employed. The high temperature cycle uses biphenyl $(C_6H_5)_2$ which absorbs heat by vaporizing at the metallurgical limit of 1000°F. The saturated vapor is then expanded through a turbine to some low pressure. It is then exhausted to a heat exchanger where it is condensed at 400°F and thereby boils water which becomes steam for an ordinary power cycle operating below 400°F. The condensed liquid biphenyl is then pumped back to "boiler" pressure and repeats the cycle.

The properties of biphenyl are:

C_p (liq) $= 0.320 + 0.001\ t$ BTU/lb°F, t in °F

C_p (sat. vapor at 1 atm) $= 1.37$ BTU/lb °F

$\log_{10} P = 7.9020 - \frac{2653}{T}$, T in °K; P in mm Hg

(a) What are the pressures in the biphenyl boiler and condenser?
(b) Construct the saturated liquid and saturated vapor curves on a T-S diagram using the data above.
(c) What is the temperature of the exhaust of the biphenyl turbine?
(d) Estimate the ideal work that can be produced by the biphenyl cycle in BTU/lb.
(e) What is the thermodynamic efficiency of this ideal cycle?

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types of problems with the emphasis on the practical type. Test problems are prepared in the same manner—the problem is submitted, discussed, modified and approved. Each instructor grades his own problem for all 200 students, regardless of section. Because the faculty take turns in proposing and grading hour tests and the final exam, individual faculty differences in emphasis of lectures, etc., are averaged out. Final course grades are assigned as follows. A total score of each student's performance in all common hour tests and the final exam is calculated. The committee examines these scores and on this basis each section is assigned a quota of A, B, C, D and fails. The individual instructor now considers other factors such as homework performance and non-common tests, etc. He is allowed to change individual student grades but his final result must closely match his assigned quota.

The honors section consists of students having a B average or better. The instructor is encouraged to consider, when possible, additional topics such as integrating factors for inexact differentials, statistical aspects of the second law, etc.; however, the common tests and homework problems keep his section in step with the others. The honors instructor enjoys his assignment but faculty assigned to other sections sometimes complain about the poorness of their students. Student response to the honors section is noncommittal.

In general, students dislike the large section apparently on grounds of previous experience. Specific complaints, such as no time to ask questions, can be reduced remarkably by assigning an excellent teacher. Then some students have even requested to be transferred to the large section during the semester. Student performance in the large section is just as good as other sections except, of course, the honors.

PROGRAMMED LEARNING

To reduce the class time spent on formal lecturing, programmed-learning material was substituted for the lectures on "temperature" in 1966 and for "basic concepts, work, and temperature" in 1967. These programs[5] thus replaced one week of lectures in 1966 and three weeks in 1967. All students were expected to have the following background knowledge:

1. Two semesters of freshman chemistry
2. Three semesters of physics (including a course on heat)
3. Three semesters of mathematics (including partial derivatives and line integrals).

Programs were designed to teach the students relevant basic nomenclature, definitions, and concepts such as system, control volume, process, exact and inexact differential, temperature, work, etc. A linear programming technique was used throughout. Direct testing of these programs was achieved by pre-test and post-test sections incorporated into the programs. Students were assigned these programs as home assignments. To facilitate program testing, students were asked to tabulate their own responses on supplied "scorecards," which were returned anonymously. Students were allowed to keep the programs. During these test periods class discussion of these topics was avoided. After collection of scorecards, students were assigned typical homework problems which were discussed fully a week later. Student performance in these problems and in hour test problems on work and temperature was judged to be at least as good as that exhibited in other areas where conventional lecture and problem discussion methods were used.

Table IV summarizes some statistical data resulting from the scorecards. Notice that a 50-minute lecture can be replaced by approximately

40 minutes' work of programmed material. Student opinion was judged qualitatively. There were no complaints that they were being "cheated" out of lecture time. Complimentary comments outnumbered complaints by a good margin.

These experiments show that factual material can be taught by carefully prepared programmed material more efficiently than by lecture. The programs were confined to "black or white," yes or no situations such as open or closed systems; exact or inexact differentials; system or surroundings. No attempt was made to program material involving judgment between "different shades of gray" such as cases when numerical integration of work expressions is superior to analytical methods.

TABLE IV.

Summary of Programmed-Learning Experiments

Program	Introduction	Work	Temperature
approx. lecture time replaced	50 min	50 min	100 min
average student time	37 min	36 min	81 min
Error rate			
pre-test	43%	61%	62%
post-test	5%	21%	16%

SUMMARY

This common course in thermodynamics offers the following advantages:

1. Students appreciate the universal importance of thermodynamics from the start.
2. The traditions and prejudices of individual departments do not escape unchallenged. Best aspects and techniques emerge.
3. The participating faculty have a unique opportunity to widen their outlook.
4. The practical-problem philosophy has been established.
5. Feasibility of employing large sections has been demonstrated.
6. Programmed-learning material can conserve valuable class time for problem discussion, etc.

These advantages are not realized without cost. The Course Chairman's job is most time-consuming; in particular, the weekly committee meetings require extensive preparation. The students' dislike of large sections can be reduced remarkably by assigning competent and experienced instructors.

Further improvement can be realized by using films and models. These media would facilitate student comprehension of engineering devices such as turbines, etc.—a source of frequent trouble.

The authors enjoyed the weekly discussions. There were differences at first, but the resultant friction when lubricated with constructive criticism produced a highly burnished product.

ACKNOWLEDGMENTS

The authors thank all faculty who participated in this common course for their cooperation. Financial support for the preparation of the programmed-learning material by the A.S.E.E. through their Programmed-Learning Project is gratefully acknowledged.

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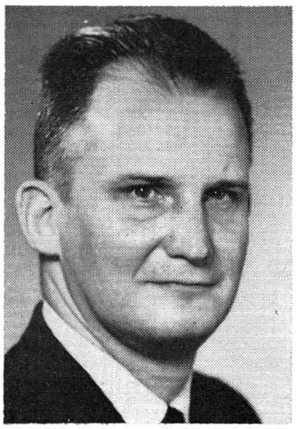
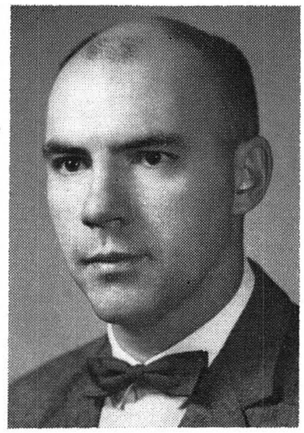
Dr. Manning received a B. Eng. (Hons.) from McGill University and M.S., M.A., and Ph.D. from Princeton. Since 1959 he has been at Carnegie-Mellon University where he is now Associate Professor of Chemical Engineering. Dr. Manning's research interests include correlation and estimation of thermodynamic properties, mixing and reaction in stirred vessels, and kinetics of metallurgical reactions and urea-hydrocarbon addution. (Photo at right.)

Dr. Lawrence N. Canjar has been the Chrysler Professor and Dean of Engineering at the University of Detroit since 1965. He was educated at the Carnegie Institute of Technology (BS '47, MS '48 and DSc '51) and joined the staff as instructor in 1950. In 1961, he became Associate Dean of the College of Engineering and Science. (Photo at left.)





Providing Meaningful
Laboratory Experience for Undergraduate Students
in Transport Phenomena

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Stated rather broadly, the objective of an undergraduate course in transport phenomena is to help students develop an understanding of, and the ability to apply, those concepts and principles which are involved in the transport of mass, momentum, and energy. Included among the concepts are the notions of velocity, stress, rate of strain, viscosity, thermal flux, temperature gradient, thermal conductivity, heat generation rate, mass flux, concentration gradient, diffusivity, and others. The principles are six in number: conservation of mass, momentum, and energy; Fick's law of diffusion; Newton's law of viscosity, and Fourier's law of thermal conduction. Since the ideas of transport phenomena are basic to many of the methods employed by chemical engineers, it is appropriate that we should exploit whatever techniques are available to accomplish our objective.

Probably without exception, the stimulus on which primary reliance is placed is the professor's lecture. In most courses, reading assignments are made from one of the standard textbooks, and homework problems are assigned to help the student gain facility in applying the principles. A conscientious professor may employ some of the film strips or short movies which are now available, and he may even present a demonstration or two. All of these are certainly valid instructional techniques, but they can be richly complemented by experience gained in a well-designed laboratory. The purpose of this paper is to describe our attempt to provide such experience for students at the junior level.

We have devised a set of experiments, each of which has to satisfy the following criteria before being accepted for inclusion in the laboratory.

1. It has to accomplish certain clearly stated objectives.
2. It has to be capable of producing experimental data which are in reasonable, say ± 10 percent, agreement with theoretical predictions.
3. It has to be relatively free of extraneous complications.
4. The equipment has to be relatively inexpensive to obtain and easy to maintain.

The methods that we have used to meet these criteria can be presented most easily by describing the first experiment.

This experiment takes two weeks to complete, although much of the first laboratory period is devoted to administrative and operational details. It concerns laminar flow in circular tubes, and its objectives are stated as follows:

1. To enable the student to visualize the velocity field for flow through a circular tube.
2. To generate some confidence in the correctness of the theory of Newtonian fluid mechanics in general and in the Hagen-Poiseuille equation in particular.
3. To develop an appreciation for the two externally applied forces to which fluids are normally subjected in tubes. These are a longitudinal pressure gradient and the force of gravity.
4. To illustrate an important limitation which must be applied to any theoretical analysis based on laminar flow. This is the transition from laminar to turbulent flow which occurs when the velocity exceeds a critical value.
5. To illustrate the use of a manometer to measure pressure in a fluid.

The principal piece of equipment used in this experiment is a constant head tank. It will be described in more detail later, but now it will suffice to mention that the outlet fitting can accept either a piece of 14 mm glass tubing, which projects up into the tank, or any other piece of equipment which terminates in ½ in.-OD tubing. In the second part of this experiment we attach a piece of 3/16 in.-OD aluminum tubing to the outlet fitting. The connection is made through a reducer and a short piece of plastic tubing which permits the angle of inclination of the 3/16 in. tubing to be changed during the experiment. The tube is fitted with pressure taps near the inlet and outlet ends. Manometer tubes which are open to the atmosphere are used to measure the pressure.

The experiment is performed in two parts. In the first part, which is the well-known Reynolds experiment, the students observe flow through a vertical section of 14 mm glass tubing. A piece of capillary tubing is used to inject a dye filament into the stream near the center of the larger tube. The flow rate can be adjusted with a valve located at the discharge end of the tube. It is possible for the students to observe that the flow is laminar at low velocities and becomes turbulent at higher velocities. The velocities are low enough that they can be measured with a graduated cylinder and a stopwatch. When a large blob of dye is injected into the stream, the students can see it deform into a well-defined parabola as it progresses down the tube. Again the velocity of the leading edge of the colored fluid is low enough that it can be measured accurately with a stopwatch and a meter stick. Hence, the student readily confirms that the centerline velocity is twice the average velocity. It is also worth mentioning that this is an esthetically pleasing experiment; the students enjoy the experiment, and it gets the laboratory off to a good start.

In the second part of the experiment, the glass tube is replaced by the 3/16 in. tube, and the manometer levels are measured at various angles of inclination and flow rates. A removable valve at the discharge end of the tube permits the flow rate and the angle of inclination to be varied independently. In analyzing their data, the students are asked to make two graphs: volumetric flow rate with the valve removed versus difference in elevation between the liquid level in the reservoir and the discharge end of the tube, and difference in manometer levels versus flow rate. If the flow is laminar and one can neglect all frictional losses except those in the tube, the first graph should be a straight line with a slope of $\pi R^4 \rho g / 8\mu L$. Actually, the resistance of the inlet fitting is not completely negligible, and the measured slope is slightly smaller than the theoretical value. Since he can see from the manometer reading that the pressure at the inlet end of the tube falls as the flow rate increases, the student readily arrives at the correct explanation for the discrepancy. The second graph is quite free from spurious effects, and the experimental data agree well with the theoretical curve. It should be noted that the difference in manometer levels is equal to the pressure drop due to viscous losses; the gravitational force exerted on the fluid in the tube is balanced by the extra gravitational force exerted on the fluid in the manometer line leading to the upper pressure tap. Providing a proper explanation for this phenomenon forces the student to think clearly about the various forces which act on a fluid in a tube.

This experiment was designed so that the flow would be laminar over most of the accessible range of velocities. At the higher flow rates, the critical Reynolds number is exceeded, which can be seen clearly by the student because the flow tends to become unsteady in the transition region. His graphs also tend to deviate from the theoretical curves at the transition point. He is asked to calculate the Reynolds number at the transition point, and values in the range from 2100 to 2500 are usually obtained. Furthermore, his experience in the first part of the experiment prepares him to accept the notion of an eddy diffusivity and an eddy viscosity, both of which greatly exceed the corresponding molecular values. Hence, he can predict qualitatively how his experimental data in the turbulent region should deviate from the theoretical curves for laminar flow.

We feel that this simple experiment illustrates many ideas that are fundamental to hydrodynamics. Since the same ideas are presented in the classroom, one can ask, "Why go to the trouble of setting up a laboratory in which experiments such as this can be performed?" The answer to this question, in our opinion, is that percepts gained through laboratory experience tend to be more vivid and lasting than those gained in the classroom. Furthermore, a higher level of problem solving is involved in analyzing experimental data than in solving most textbook problems. The student has to devise the problem that pertains to his particular experiment before he can solve it. He has to recognize what is important and what can be neglected. And finally, he profits by his own mistakes if he is persistent enough to bring the experimental and theoretical results into agreement. We have found that the last point is very important, but it can only be realized if the experiment is designed in such a way that accurate data can be obtained.

If a laboratory such as this is to complement the lecture course, timing is important and all of the students must be doing the same experiment at the same time. Adequate access to the equipment can be achieved only if the students work in groups of two or three. This means that as many as ten complete sets of equipment may be required at a large university. We have tried to make this possible by designing small pieces of apparatus, individual parts of which can serve many purposes.

For example, the constant head tank mentioned earlier was made from a three liter stainless steel beaker. Two holes were cut in the bottom of the beaker. An overflow pipe was soldered into one of the holes, and a one-half inch bulkhead fitting of the Swagelok type was fastened into the other hole. An O-ring groove, cut into the inside surface of the bulkhead fitting, permits a water tight seal to be maintained around the piece of 14- mm glass tubing which passes through the fitting. Of course, any other piece of equipment terminating in one-half tubing can also be attached to the fitting. This feature enables us to use the constant head tank in five distinct experiments.

The second hydrodynamics experiment is a tank-emptying experiment for which it is only necessary to turn off the inlet flow line. In the third experiment, the behavior of a siphon is studied, and the constant head tank is used again as a reservoir. We also do a heat transfer experiment in which transient heating and cooling of the contents of the tank are studied. Although the details have not been completely worked out, we also plan to devise a transient state mass transfer experiment.

In the case of the heating experiment, the heater is a small finned-tube heat exchanger, which passes through the Swagelok fitting in the bottom of the tank, and is sealed by the O-ring. The lower end of the heater fastens directly onto a small electrically heated boiler that can provide over a kilowatt of power. The boiler also serves several purposes. In addition to providing steam for the tank heating experiment, it provides steam for a thermal conductivity cell in which heat transfer through composite slabs is studied. It also provides steam for the annular region of a small concentric tube heat exchanger.

By reducing the size of our equipment, keeping it relatively simple, and making the more expensive pieces perform multiple functions, we have been able to obtain the necessary equipment with a rather modest capital outlay. It is also worth noting that, since the equipment is small in size, finding adequate storage space is not a problem.

The experiments are performed in one bay of a large laboratory. This bay has been fitted with a number of "distillation racks." Electrical power, water, air, and drains are provided at each of the racks. The equipment can be mounted easily on a rack and left there for several days if necessary. This permits the students to come back and repeat part of an experiment or obtain additional data. Hence, they are not as pressed for time as they might otherwise be, and they can be held responsible for the accuracy of their observations.

In this brief paper an attempt has been made to describe the approach that we have used to provide meaningful laboratory experience for an undergraduate class in transport phenomena. A considerable amount of effort has already gone into this project, and more will be required before a really satisfactory result is achieved. Hopefully, others can benefit from our experience as we have benefitted from the experience of those who preceded us.

Acknowledgement. It is a pleasure to acknowledge the contributions made to this project by three of the author's colleagues, K. B. Bischoff, N. F. Brockmeier, and R. S. Schechter.

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Mass Transport Phenomena In

The Human Circulatory System*

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The value of biological research in a chemical engineering graduate program is discussed by taking examples from the mass transport phenomena occurring in the human circulatory system. The particular points stressed are the broad range of such problems from molecular diffusion to artificial organ design, the relevance of the problems to traditional areas of engineering concern, and the value of research in the area as a technique for training engineering students.

The programs for meetings held over the past few years by the American Institute of Chemical Engineers and the American Society for Engineering Education bear witness to the emergence and persistent growth of interest in the interaction of engineering and biology. Almost every meeting has had at least one session devoted to some aspect of this interaction.

There are many possible explanations for such a development, all of them probably true to some extent. In the last decade, advances in the biological sciences have been the most dramatic in the scientific world and have called particular attention to the field. Morover, the social and humanistic awareness which seems to characterize the 1960's suggests that many people may find greater satisfaction in problems whose solutions appear to them to contribute directly to human welfare. Finally, the recognition and development of new kinds of unifying principles in chemical engineering, such as the transport phenomena, have greatly increased the range of applicability of chemical engineering techniques and perhaps have stimulated many of us to attempt to prove their usefulness in the unfamiliar and challenging areas of biology.

However, speculating on the reasons for the growth of biological engineering, while interesting, is not my purpose in this discussion. In keeping with the subject of the meeting, it would seem more appropriate to consider what effect this new area can or should have on graduate chemical engineering research. It is necessary to recognize that there are two extremes of organi-

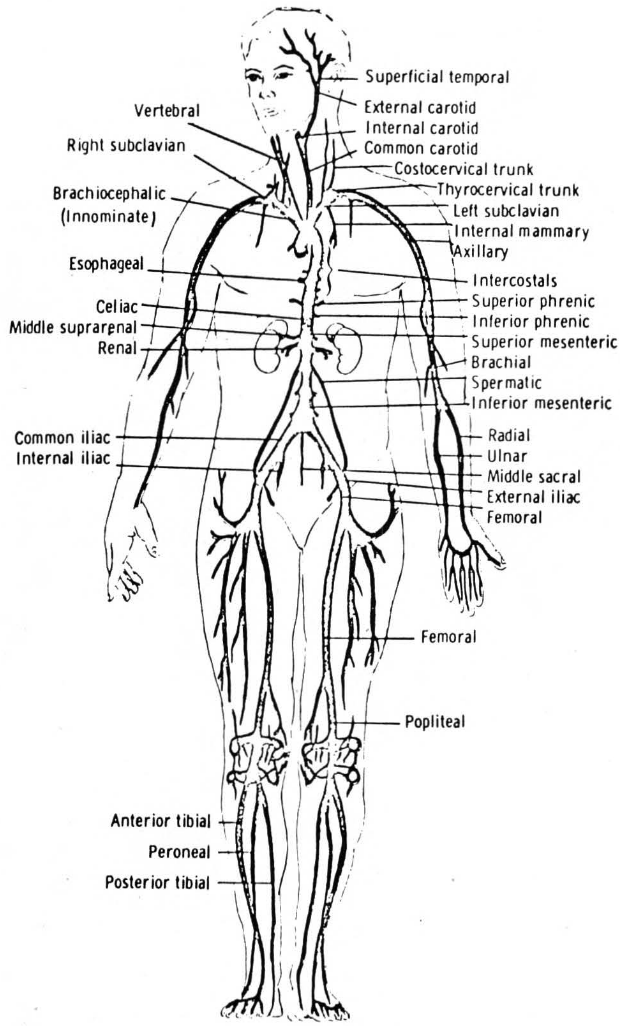
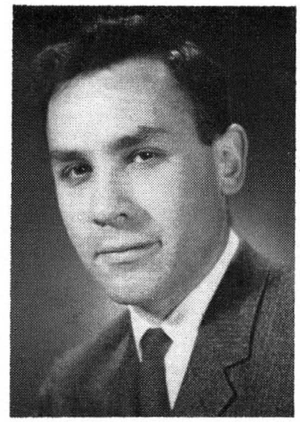


Fig. 1.—Human circulatory system.
From Chaffee and Greisheimer, *Basic Physiology and Anatomy*, with permission of J. B. Lippincott Co., Philadelphia.

*Presented at the Annual Meeting of ASEE, June 19-22, 1967.

Dr. Keller did his undergraduate work at Columbia University and then spent four years in the Navy assigned to the Atomic Energy Commission. In 1959 and 1960, while in the Navy and attending the Johns Hopkins University part time, his interest in biologically-oriented problems developed. His full-time graduate research began in 1961 at Hopkins, centered on the phenomenon of augmented oxygen diffusion in hemoglobin solution. Since 1964 he has been an Assistant Professor of Chemical Engineering at the University of Minnesota and has continued and expanded his research interests in transport processes in biological systems. He is now directing research in diverse problems from protein diffusion studies to blood oxygenator design.



zation between which most bioengineering programs lie: the independent, formal bioengineering program, functioning through an interdisciplinary group joined together by a common interest in biology and the informal group whose research and teaching simply constitute one special area of a chemical engineering department. There is certainly no unanimity among people working in the field as to which, if either, of these extremes is the better for effective biological research, but obviously only the latter arrangement can benefit a chemical engineering department directly. Therefore my remarks will relate to this latter arrangement. In particular, I would like to illustrate:

a. The relevance of biological problems to the traditional areas of chemical engineering concern.

b. The wide range of problems in biology to which engineering analysis can be applied effectively.

c. The mutual benefit to biology and engineering which can result when engineers attack such problems.

d. The didactic value of having graduate students work in the biological area.

These points are best illustrated by example and the human circulatory system is a convenient one.* For many purposes the human body can be considered to be a highly complex chemical plant utilizing the energy of combustion to synthesize biological materials and to do work. The sites of reaction are distributed throughout the body and the circulatory system serves to deliver the reactants and remove the waste products; since the body functions isothermally, it must also remove excess heat. In addition the system serves a host of secondary functions: maintaining the proper water and salt content, distributing drugs and natural antitoxins, maintaining its own integrity by sealing "holes," adjusting pH to an optimal level, etc.

The magnitude of the job which the circulatory system must perform is evident from its design parameters. There are 5 to 6 liters of blood in the average human being (wholly contained within the circulatory system). The system's pump, the heart, has a capacity of about 6 liters/minute so that the circulation time through the body is slightly less than 1 minute. The average adult (70 kg) consumes about 14 liters (STP)/hr of 0_2 and releases about the same amount of CO_2, all of which is transported through the circulatory system.

The form of the system, as usually depicted in a medical text, is shown in Figure 1. Its most obvious characteristic is its high degree of branching, with main vessels branching in steps to large numbers of smaller vessels. However, from the point of view of mass transport, it is equally important to note that the system is bounded and that transfer into and out of the organs and tissues of the body must occur across the walls of the circulatory system. Such transfer takes place almost entirely in that region of the system made up of a network, or bed, of thin-walled, narrow bore tubes called capillaries. These capillaries are 10μ in diameter, have a wall thickness of about 1μ and a length of about 1 mm. Capillary beds are found in every organ and tissue of the body; since they are too small to be distinguished individually by the naked eye, it often appears that the blood is dispersed in a diffuse, continuous distribution through the tissue.

There are about 10^9 capillaries in the body so

*A useful and interesting introduction to the circulatory system is provided by Alan Burton's recent monograph.[1]

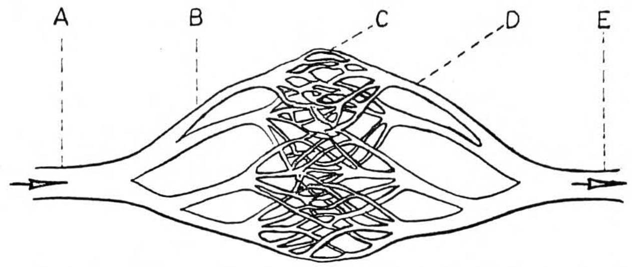


Fig. 2.—Schematic flow path to and from a single capillary bed. A. Artery; B, Arterioles; C, Capillaries; D, Venules; E, Vein.

that, despite the small size of each one, the total surface area available for transfer is about 340 ft^2. The extremely high surface to volume ratio in the system is evident from the fact that even with this large surface area, the capillaries contain less than a liter of blood at any instant. Transfer is so efficient that the residence time of blood in any capillary bed is only about 1 second.

The capillary beds are local structures and the rest of the circulatory system can be thought of as the piping to connect these structures and to carry materials and heat from one part of the body to another. The branching and progressive decrease in diameter of the system's piping is necessary to connect the central, large branches and the distributed, small branches. In Figure 2, one complete network is shown. Blood flows from the heart through the main artery (about 1″ in diameter), branching to smaller terminal arteries, still smaller arterioles, and finally to capillaries. After exchange has taken place in the capillaries, the blood flows to larger venules, still larger veins, and finally to the principal veins of the body which lead back to the heart.

One of the key steps in defining engineering problems in a biological system is that of translating the description of the system into engineering terms. Consider, for example, how the schematic diagram of the circulatory system could be redrawn to the more familiar sort of schematic shown in Figure 3. The system is depicted as simply a set of single-pass shell (tissue) and tube (capillary) mass and heat exchangers connected in parallel. The arterioles and venules are the headers and the small arteries and veins are the connections to the main pipes. Pumping is provided by a double reciprocating pump and is, therefore, pulsatile. O_2 enters the system and CO_2 leaves the system in the exchanger called the lungs. Water, salt, and waste are removed through the exchanger called the kidney. On the shell side of the other exchangers, various chemical reactions take place which consume oxygen and produce carbon dioxide (muscles, brain, etc.). Heat is rejected from the body in the capillary beds, or exchangers, located in the vicinity of the outer surface of the body. Note that the heart and lungs are the only two organs through which *all* of the blood passes on each circuit.

The actual mass transport and transfer taking place in each of these units is not, of course, as simple as this picture would suggest. However, it does illustrate the transfer functions involved and thereby provides a basis for analyzing the behavior of each organ. It also establishes the functional requirements of any replacement or prosthetic unit, the design of which is one of the important areas of biological engineering.

If we proceed further and examine some of the transport and transfer processes in more detail, the efficiency and complexity of the circulatory system become evident as well as the range of challenging research problems to which chemical engineers have applied and should apply themselves.

Consider, for example, the process of oxygen transfer in the lungs. The blood, depleted of oxy-

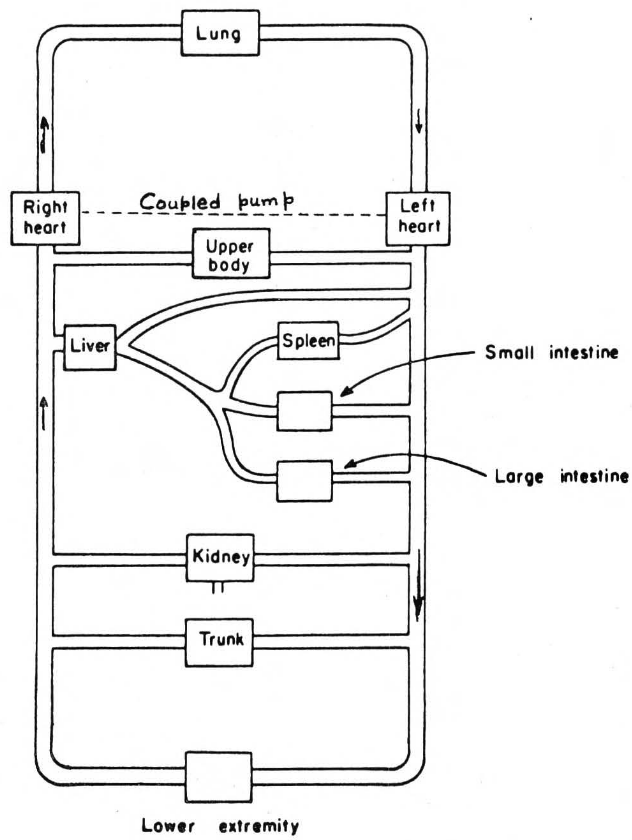


Fig. 3.—Schematic diagram of circulatory system.

gen by the tissues, enters the lung capillary bed at an oxygen tension* of about 60 mm Hg. It takes up oxygen and leaves the lungs at a tension of about 100 mm Hg. If oxygen uptake by the blood were limited to that which could be physically dissolved, a simple mass balance could be written to calculate the blood flow rate necessary to absorb the 14 liters (STP)/hr needed by the body for metabolism, i.e.

$$Q[(CO_2)_{out} - (CO_2)_{in}] = \frac{14}{60} \frac{\text{liters (STP)}}{\text{min}}$$

The concentrations can be calculated approximately from the physical solubility of oxygen in water (0.024 liters (STP)/liter H_2O atm). This equation can then be solved for Q, the volumetric flow rate, yielding a value of 185 liters/min, 31 times the actual flow rate available. Thus the circulatory system must have recourse to something other than the simple physical solubility of oxygen in order to absorb a sufficient amount of oxygen. This is provided for in blood by the large protein molecule, hemoglobin, which can combine reversibly with four oxygen molecules. Hemoglobin is present in blood to the extent of 15 gms/100 ml and, based on its molecular weight (68,000), if it is completely oxygenated, approximately 50 times as much oxygen can be carried in this combined form as is carried in the physically dissolved form. The combination must, of course, be reversible in order for the oxygen to be available to the tissues for metabolism. In

*Oxygen tension, in physiological parlance, is that concentration of oxygen in liquid which is in equilibrium with a gas phase having an oxygen partial pressure of the value stated.

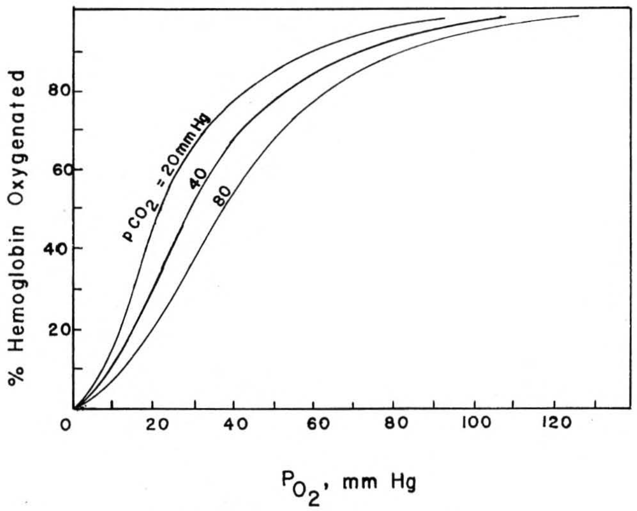


Fig. 4.—Typical equilibrium curves.

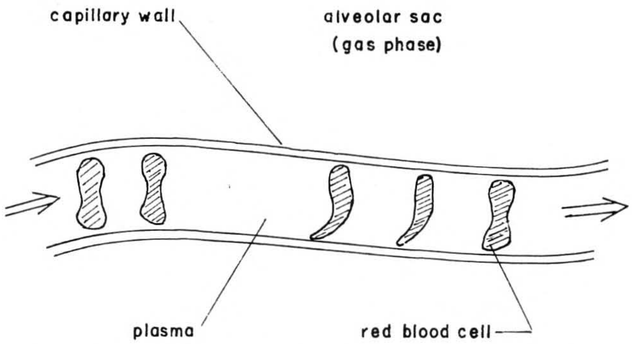


Fig. 5.—Red blood cells passing through a capillary.

fact, the equilibrium between hemoglobin and oxygen is not only reversible, but shifts conveniently to facilitate absorption and desorption. This is illustrated in Figure 4, which shows some typical oxygen-hemoglobin equilibrium curves. Note that at low CO_2 concentrations (which would exist in the lungs), the affinity of hemoglobin for oxygen is large and the hemoglobin is close to fully oxygenated at an oxygen tension of 100 mm Hg. However, at high CO_2 concentrations, such as those which are found in the body tissues, the affinity decreases and the degree of oxygenation for a given oxygen tension decreases markedly so that oxygen is readily available to the tissues.

Hemoglobin is not distributed homogeneously throughout the blood; it is contained in extremely high mass concentration (35 gms/100 ml) within the red blood cells which constitute 40-45 percent by volume of the blood. These red blood cells are biconcave discs approximately 8μ in diameter and varying from 1μ to 2.5μ in thickness. Thus, their diameter is almost equal to the inside diameter of the capillaries. In fact, in passing through the capillaries, the red blood cells line up in single file and slip through as shown in Figure 5. For the capillaries of the lung, note the complex diffusional process involved in getting oxygen from the gas sacs of the lung (alveoli) to the hemoglobin with which it must react. The oxygen must diffuse across the capillary wall, through a layer of plasma, across the red blood cell membrane, and then through the hemoglobin solution with which it simultaneously reacts. This gives rise to several interesting and not completely solved mass transfer problems. For example, which of these resistances is limiting on the total rate of uptake (or desorption) of oxygen? What path does the oxygen take in the plasma? Do the convective

For many purposes the human body can be considered to be a highly complex chemical plant utilizing the energy of combustion to synthesize biological materials and to do work.

mixing patterns which must be set up in the plasma between cells increase the uptake rate? Is the red blood cell membrane equally permeable over its entire surface or do materials cross it in localized regions? What bearing, if any, does the shape of the cell have on mass transport?

The answers to such questions have an obvious bearing on the design of devices to replace inoperative transfer organs in the body. They may also be useful in the diagnosis of pathological (disease) conditions. But one of the important lessons in the development of engineering has been the recognition that it is possible to generalize results, to see the phenomenological similarities between processes in quite different systems and to relate the experimental and analytical results of one system to another. Thus, the results of studies of mass transfer across the membrane of a red blood cell should bear some relation to the problems of supplying nutrients to microbial cultures. They should also complement the work of cell physiologists studying general membrane properties. Similarly, information on diffusional behavior in hemoglobin is of interest to molecular biologists and biophysicists interested in characterizing macromolecules. Therefore I think it is necessary to avoid the narrow interpretation that biological engineering refers to clinically directed, biomedical problems. I have, in fact, avoided the use of the term "biomedical engineering" for precisely this reason.

A reasonable approach to understanding the uptake of oxygen in blood is to study separately each of the diffusion resistances involved. The easiest of these to study is the red blood cell (contents and membrane) since it can be easily removed and studied outside the body, or *in vitro*. Much of the early work in this area was done by F. J. W. Roughton who published a useful review article some years ago.[2]

In the cell itself, the transport process occurring is one of diffusion accompanied by reversible chemical reaction. In this context, it is analogous to such industrial processes as the absorption of chlorine by water which has been studied extensively by Vivien and Brian.[3] Therefore this is a typical problem in which the results of studies on the biologically important system have applicability to traditional engineering systems. Because the hemoglobin-oxygen reaction is accompanied by an easily detectable color change, it provides a simple experimental system and we are now using it to study unsteady gas absorption with reaction.

Studies on the hemoglobin-oxygen system have uncovered another mass transport phenomenon of engineering interest. In 1959 and 1960, Wittenberg[4] and Scholander[5] discovered that if a Millipore filter soaked in hemoglobin solution were placed between two gas chambers at different pressures, the steady-state diffusion of oxygen exceeded that of nitrogen by severalfold in certain concentration ranges although their driving forces were the same. This intriguing phenomenon has been studied in some detail by several workers, including Friedlander and myself[6,7] and the mechanism is fairly clear. Oxygen entering the liquid phase will combine reversibly with hemoglobin. Because of the equilibrium between combined and uncombined form, the concentration of oxygenated, or oxyhemoglobin, will depend upon the local concentration of oxygen. Since an oxygen gradient exists across the system, in certain ranges of concentration an oxyhemoglobin gradient will also exist and the total flux of oxygen will be the sum of the two resulting fluxes. The interesting engineering aspect of this is that such a system can be used effectively to separate gases if a reversibly reacting species can be found which reacts selectively with one of the gases. At General Electric, Ward has been examining such separation systems.[8]

It is necessary to avoid the narrow interpretation that biological engineering refers to clinically directed, biomedical problems. I have, in fact, avoided the use of the term "biomedical engineering" for precisely this reason.

In the course of our investigations into this phenomenon, it was necessary to determine the diffusion coefficient of hemoglobin as a function of concentration. The subject of diffusion of large molecules in liquids at other than infinite dilution is one for which there are relatively few data and no useful theory. Yet, almost all

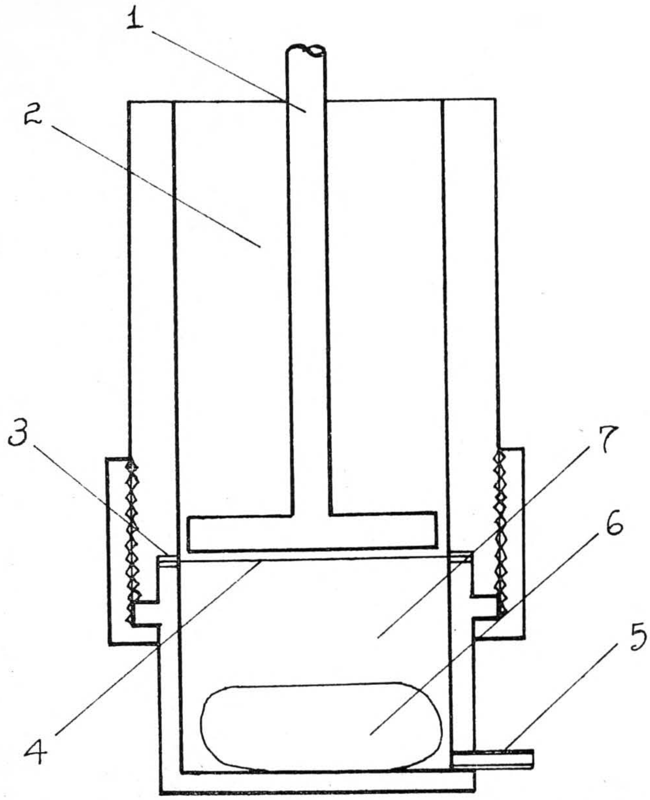


Fig. 6.—Diaphragm cell for methemoglobin diffusion coefficient measurements: 1,Stirrer; 2, Upper compartment; 3, Teflon gaskets; 4, Millipore filter; 5, Sample inlet; 6, Magnetic stirring bar; 7, Lower compartment.

living cells contain at least 20 percent by volume of large protein molecules, so that such data are necessary if intracellular diffusion problems are to be examined. We have developed a modified Stokes diaphragm diffusion cell which allows rapid measurement of protein diffusion coefficients[9]. In the cell, shown in Figure 6, diffusion takes place only in the thin, Millipore filter separating the two reservoirs. Because the filter is thin, steady state is achieved rapidly and diffusion fluxes are large enough to be measured despite the large size and correspondingly small diffusion coefficients of protein molecules. One feature of proteins which makes them desirable for such studies is the fact that radioactive tracers can be attached to them easily, thereby facilitating tracer diffusion measurements. This obviates the need for converting integral diffusion coefficients to differential diffusion coefficients, a process which has inherent inaccuracies.[10]

Some of our results with hemoglobin are plotted in Figure 7. It is interesting to note that at high concentrations, the diffusion coefficient decreases linearly with concentration. Other available data indicate similar behavior and have led us to a simple phenomenological theory for predicting diffusivities of proteins as a function of concentration. A question not yet investigated, but of great interest, is whether or not, as a result of the small size of the cell, proteins exist *in vivo* as liquid crystals with markedly different diffusional properties.

The membrane which forms the boundary of the red blood cell represents a separate area of investigation. Electron micrography has shown that the membrane is about 100 Å thick and composed of protein and lipid (fat-soluble) material. While there is still basis for argument, the so-called unit membrane shown in Figure 8 is often accepted as representative of the membrane structure. It is simply a bimolecular lipid film, oriented with polar ends outward toward the aqueous phases and non-polar ends inward, and sandwiched between protein layers. While the picture fits morphological evidence, it is of little help in understanding or choosing a model for explaining the transfer function. For example, should the membrane be modeled as a matrix of pores in an otherwise impermeable structure? This might explain a selective permeability based on the size of the diffusing molecule. On the other hand, if the membrane were modeled as a continuous, non-polar phase, selectivity would result from variations in phase partition coefficients among different molecules. Indeed, both kinds of selectivity occur and suggest that a more complex description is necessary to understand membrane function adequately.

Perhaps the most intriguing aspect of membrane transport is suggested by the observed distribution of cations inside and outside the red

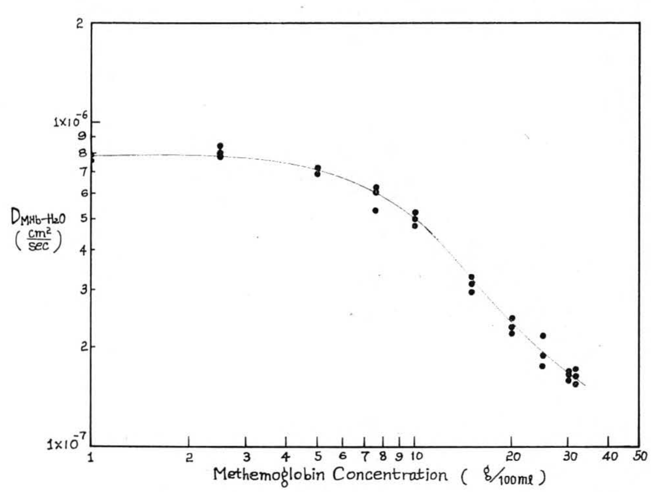


Fig. 7.—Diffusion coefficient of methemoglobin at 25°C.

blood cell. Inside the cell, the concentration of K^+ is 0.136 M while that of Na^+ is only 0.019 M. Outside the cell, the situation is reversed with the K^+ concentration only 0.005 M and the Na^+ concentration 0.112 M. Yet tracer studies show that both cations exchange across the membrane and, moreover, if an excess of K^+ is placed in the plasma, it is quickly taken in by the cell. The flux is thus in the opposite direction from that expected by simple diffusion theory. Close investigation shows that this flux is accompanied by chemical reaction in the membrane which provides the energy necessary to satisfy thermodynamic considerations. However, we are still far from understanding the mechanisms of this "active transport." A good deal of effort has been spent in describing the phenomenon in the formalism of irreversible thermo-dynamics,[11] but this simply begs the question. Since membranes are now thought to be responsible for most of the organizing and control functions of biological systems, research in this area is of great current importance.

Still another kind of mass transport exhibited by the circulatory system is that resulting from the flow patterns in the larger vessels. Throughout most of the circulatory system, the Reynolds' number is less than its critical value and flow is laminar. The laminar velocity profile is essentially parabolic, although somewhat flattened at the center because of the pulsatile and non-Newtonian character of blood flow. Normally in laminar tube flow, radial diffusion occurs only through Brownian motion. Blood, however, is particulate in nature and the red blood cells rotate as they flow under the influence of the velocity gradient. As they rotate they stir the plasma in their vicinity and thereby cause a mixing motion which can be interpreted as a particle-induced eddy diffusivity. This phenomenon should augment the radial transport of species dissolved in the plasma and, indeed, preliminary experiments indicate that it does.[12] We are now utilizing the effect to decrease the resistance of the plasma to diffusion in an artificial blood oxygenator. We hope that this will allow us to decrease the required surface-to-volume ratio of the oxygenator, an important design improvement. There is also evidence that the phenomenon may aid in understanding some of the transport mechanisms involved in arteriosclerosis. Finally, it seems possible that this phenomenon can be put to use in certain industrial processes. For example, if a diffusion limited wall-catalyzed reaction takes place in a continuous flow tubular reactor, it may be possible to increase its efficiency by introducing a suspension of inert particles to decrease diffusion resistance.

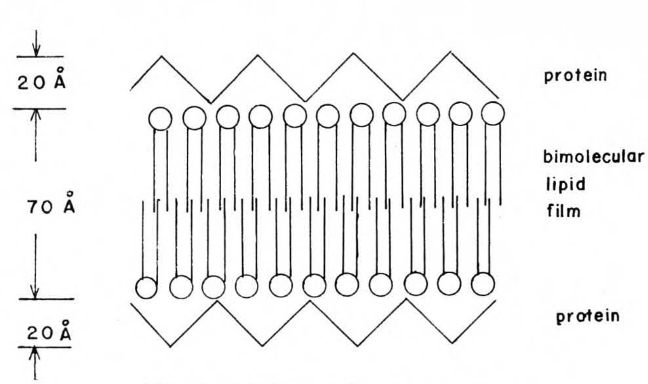


Fig. 8.—Unit membrane structure.

I have avoided a direct discussion of the design of artificial organs not because it is less important than these others, but because it is perhaps the most obvious area for engineering participation in biomedical research. It is, of course, profoundly important, and has given rise to many interesting problems in trying to duplicate the efficient transfer processes of the body and in trying to find materials compatible with blood. A review of the early design work in heart-lung assists is given by Galletti and Brecher[13] and a running account of the current state of things is available in the *Transactions of the American Society for Artificial Internal Organs.*

So much then for this cursory look at the range of mass transfer problems in the circulatory system. It is, I think, clear that these problems are the legitimate concern of chemical engineers. I am of the opinion that they are also challenging and interesting. Finally, I would like to stress my belief that they have a unique value in the training of chemical engineers. The language of biologists is not the language of engineers. Therefore the researcher must begin by distilling from the available biological descriptions the engineering essence of the problem. To accomplish this, he must first understand quite clearly the nature of engineering problems and the techniques of modeling. This adds an important facet to the training of researchers in an area which is often neglected. I think the result is not simply someone trained to examine biological problems, but in fact, someone better trained to examine any engineering problem.

(References listed on page 45).

Dynamic Optimization

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During the implementation of any computer control procedure, it is necessary to determine dynamically the desired "steady-state" condition, and then to determine the best way to control the process so as to arrive at the desired steady state in some optimal fashion. Such a procedure is termed dynamic optimization. This paper presents a method for such dynamic optimization, easily applied to computer control, and applicable whether or not the uncontrolled system is stable at the desired steady state.

INTRODUCTION

Dynamic optimization of a chemical or petroleum process can be defined as the problem of dynamically determining the desired "steady-state" condition of that process and then determining the best way to control the process so as to arrive at this desired steady state in some optimal fashion. Such a control procedure normally requires an on-line, real-time digital computer to monitor the process and to perform the necessary optimization calculations as they arise. Hence, it is obviously a form of computer control.

The mathematical formulation of the dynamic optimization problem involves the extremization of some integral criterion function over time, subect to constraints which arise from the chemistry and physics of the process being controlled. Several methods of attacking such a problem have previously been proposed, including classical calculus of variations, Pontryagin's maximum principle, dynamic programming, and linear programming. However, there are limitations to each of these methods, which tend to make them impractical for the general case. The difficulty with both the calculus of variations and the Pontryagin methods is that the optimization requires the trial and error solution of a two-point boundary value problem. With dynamic programming the dimension of the system becomes limiting because of computer storage requirements, and with linear programming trouble is often encountered when attempts are made to linearize over a wide range of operating conditions.

It has been shown[1,2,4] that Lyapunov's direct method for stability analysis can be extended to apply to the dynamic optimization problem. Such a method can be utilized in practically all known situations, with either linear or nonlinear system equations, as well as those involving constraints on the system variables. No trial and error solutions are required. The present paper presents the basic principles of Wanninger's approach,[3] utilizing Lyapunov's direct method for stability analysis, followed by the results of its application to the control of a portion of the Williams system,[5] originally proposed as a model for computer control studies.

LYAPUNOV'S DIRECT METHOD[4,5]

Considerable effort has been expended in the design and analysis of stable control systems. One useful technique for the stability analysis of a nonlinear system is Lyapunov's direct method, as presented by Bertram and Kalman[1] and applied by Koepcke and Lapidus[2] and others. The gist of this method is as follows:

Define $V(X)$, such that:

1. $V(X) > 0, X \neq 0$
2. $V'(X) < 0, X \neq 0$ (for continuous time)
   or
   $\Delta V(X) < 0, X \neq 0$ (for discrete time)
3. $V(X)$ continuous in X
4. $V(X) \rightarrow \infty$, as $||X|| \rightarrow \infty$

If such a function can be found, $X = 0$ is a stable equilibrium point, and the system is asymptotically stable in the large about $\mathbf{X} = 0$. It is called a Lyapunov function, after the man who developed this criterion. Note that the equations describing any particular system can be transformed by a change of variables such that $X = 0$ is the desired operating point.

In utilizing Lyapunov's direct method for the dynamic optimization problem, the steady-state and unsteady-state portions of the problem are considered separately. Given a set of costs and an optimization criterion, the optimal steady-state point is first determined, independent of transient operation. Then, knowing the desired steady-state point, the Lyapunov method is utilized to determine the best control sequence to follow as the process moves toward the desired steady-state condition.

OPTIMIZATION PROCEDURE

Consider a linear system, involving state vector $\mathbf{X}$ and control vector $\mathbf{U}$, according to the following equation:

$$\mathbf{X} = \beta \mathbf{X} + \epsilon \mathbf{U}$$

It has been shown[4] that the solution to the discrete form of this matrix differential equation is as follows:

$$\mathbf{X}\ (t_0 + \tau) = \Phi\ (\tau)\ \mathbf{X}\ (t_0) + \Psi\ (\tau)\ \mathbf{U}\ (t_0)$$

where τ is the sample interval, and $\Phi\ (\tau)$ and $\Psi\ (\tau)$ are functions which can be numerically determined from the matrices β and ϵ of the linear, or linearized, system. An appropriate transformation is assumed such that $\mathbf{X} = 0$ is the desired steady-state point and $\mathbf{U} = 0$ is the steady-state control vector.

Now, choose $V\ (\mathbf{X}) = \mathbf{X}^T\ \mathbf{Q}\ \mathbf{X}$, where $\mathbf{Q}$ is a positive definite matrix.

Define $\mathbf{X}\ (t_0 + k\tau) = \mathbf{X}\ (k)$.

Then: $V\,[X(k)] = \mathbf{X}^T\ (k)\ \mathbf{Q}\ \mathbf{X}\ (k)$, and:

$\Delta V\,[X(k)] = \Delta V(k) = V\,[X(k + 1)] - V\,[\mathbf{X}(k)]$
$= X^T(k + 1)\ QX\ (k + 1) - X^T(k)QX(k)$

From above solution:

$$X(k + 1) = \Phi(\tau)X(k) + \Psi(\tau)\mathbf{U}(k)$$

Therefore:

$$\Delta V(k) = X^T(k)\Phi^T(\tau)Q\Phi(\tau)X(k)$$
$$-X^T(k)QX(k) + U^T(k)\Psi^T(\tau)Q\Psi(\tau)\mathbf{U}(k)$$
$$+ 2U^T(k)\Psi^T(\tau)Q\Phi(\tau)X(k)$$

Consistent with the Lyapunov stability criterion, best control results when the control vector is chosen so as to make $\Delta V(k)$ as negative as possible. If this is done, it has been shown[4] that:

$$\mathbf{U}\ (k)^{\text{opt}} = \mathbf{D}\ \mathbf{X}\ (k)$$

Where $\mathbf{D} = -[\Psi^T(\tau)\mathbf{Q}\Psi(\tau)]^{-1}\Psi^T(\tau)\mathbf{Q}\Phi(\tau)$

The choice of the positive definite matrix $\mathbf{Q}$ is not unique, and it is one of the "control parameters" available to the engineer. Any choice of positive definite $\mathbf{Q}$ guarantees a proper scalar function $V\ (\mathbf{X})$, and makes $V\ (\mathbf{X})$ directly related to the integral error squared for the system. The relative magnitudes of the elements of Q markedly affect the control action, with the result that the best $\mathbf{Q}$ is the one which gives the best response to the various types of upsets which may be expected to occur.

It should be noted that the method here presented does not select the control $\mathbf{U}(k)$, $k = 1, \ldots, h$ so as to minimize $\int_0^{n\tau} \mathbf{X}^T\mathbf{Q}\mathbf{X}d\mathbf{X}$ as would be "mathematically optimal" for the time period $(0, n\tau)$, but instead merely selects each $U(k)$ so as to minimize the additional contribution to the integral error squared during the k th interval. This may introduce some deviation from truly optimal behavior, but the advantages of the proposed procedure outweigh this possible limitation, from the viewpoint of application. These advantages include: (1) the elimination of the two-point boundary value problem, and its associated computational difficulties; and (2) the consideration of stability via the Lyapunov function, with the result that the system always heads toward the desired point. Further work is necessary to prove the general applicability of the method, but it seems to work well in many cases of practical interest (see below).

APPLICATION

A previous paper[4] presented a detailed report of the application of the proposed procedure to the control of a simple continuous stirred tank reaction in which a second-order reversible reaction is being carried out. Several types of upsets were used and excellent behavior was obtained for each. Modifications of the $\mathbf{Q}$ matrix allowed flexibility of control by shifting the control emphasis from one variable to another.

The method has also been applied to the control of a more realistic chemical reactor system, as originally proposed by Williams and Otto[5] for

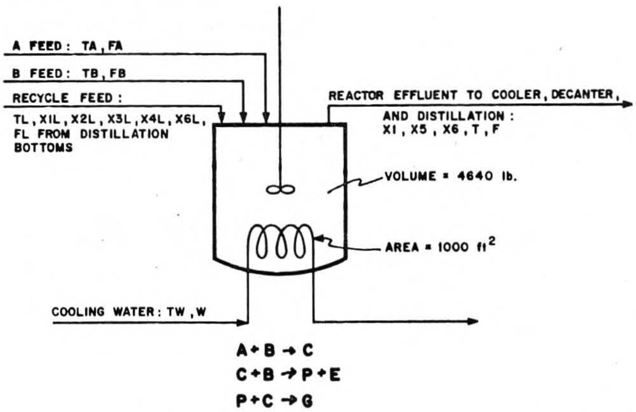

Fig. 1.—Schematic Diagram of Williams Reactor.

computer control studies. Details of the reactor are shown in Figure 1. Six material balances and one energy balance can be written around the reactor, but it has been shown[3] that only three of the material balances are independent. Hence, the resulting system differential equations involve four state variables (X_1, X_5, X_6, and T) and as many as three control variables (F_A, F_L, or W). See Reference 3 for details of these equations.

The numerical work involved in this more recent application was carried out on the digital computer at the Northwestern University Computer Center. Briefly, the procedure was as follows. First the nonlinear differential equations describing the reactor system were simulated via a Runge-Kutta integration routine. Then the system equations were linearized for use in the control scheme. The reaction model was operated, various upsets were applied, and the Lyapunov control actions were computed and fed to the reactor at sample interval times. An interval time of 0.01 hours (of reactor time) was found to give satisfactory control of most upsets considered, although it was necessary to go to $\tau = 0.001$ hour to get satisfactory control against step changes in recycle concentration.

Based on previous work with the simple second-order system, it was decided to choose **Q** equal to the identity matrix, after suitable normalization of the state variables. This choice of **Q** results in a Lyapunov function which is essentially equivalent to the sum of the squared error of the state variables—a common criterion for optimal control. Minimizing the derivative of the Lyapunov function is then equivalent to minimizing the squared error of the system during the next time increment. Such a choice of **Q** seems like a reasonable one for any system.

Three different control variables were investigated: (1) flow rate of cooling water; (2) flow rate of A feed, keeping total feed constant; and (3) recycle rate, keeping A and B feed rates constant. It was found that with the exponential behavior of temperature on reaction rate, control of cooling water alone gave good behavior. The addition of a second or third control variable to help control concentration did little to improve the overall response. Hence, the particular runs reported here used only cooling water rate as the control variable.

Figure 2 illustrates the response of the Williams reactor to a step change of 10°R in the temperature of each feed stream. The reactor was at steady state at time = 0, when the step was applied. It is seen that the uncontrolled reactor responded by moving away from the desired operating point, and continued moving away as would be expected for an unstable system. The Lyapunov controlled response, however, was stable, and the reactor remained at the desired operating point.

Figure 3 shows the response to initial offsets of 0.01 in each of the state concentration variables and of 10°R in reactor temperature. A sub-

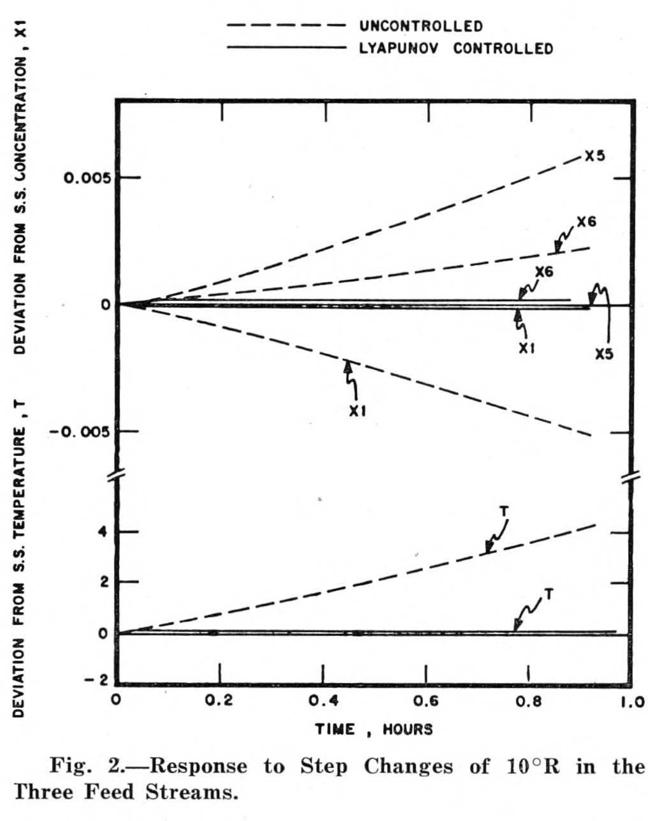

Fig. 2.—Response to Step Changes of 10°R in the Three Feed Streams.

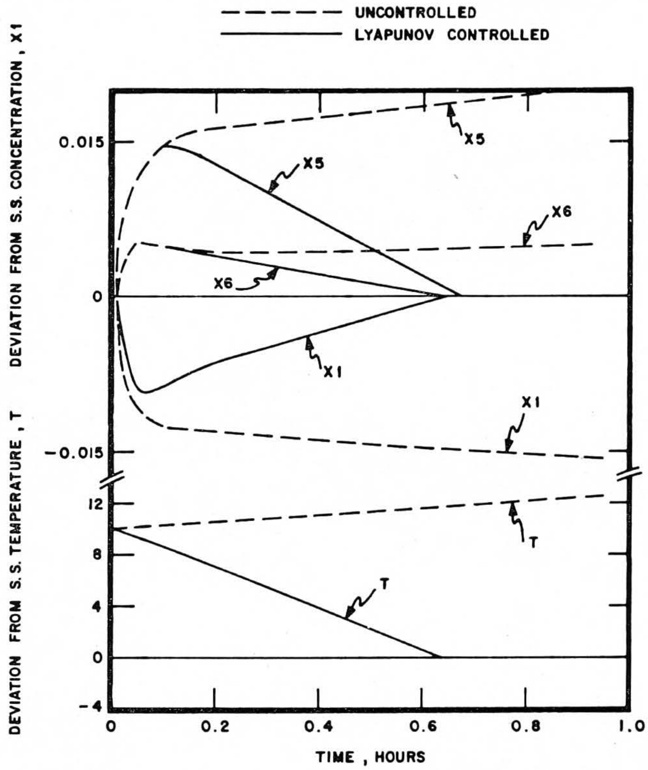

Fig. 3.—Response to an Initial Offset in Reactor Temperature and Concentrations.

stantial final error, or offset, occurs for the uncontrolled reactor. The Lyapunov controlled response is limited by the bound on the cooling water rate. If the cooling water capacity were increased, the system would return to the steady-state point more rapidly.

Figure 4 shows the response to a step change in recycle composition as well as inlet feed temperature. The recycle composition was changed such that components 1 and 6 were increased by 10 percent each and component 2 was decreased by a corresponding amount. Again, the uncontrolled response was unstable, while the controlled response was excellent for such a large change. The sample time, τ, was decreased to 0.001 hours for this case.

A conventional three-mode control system was also designed for the Williams reactor and operated to give data to compare with the Lyapunov control behavior. The reactor temperature was used as the measured variable, and the entire system was simulated on the digital computer, using the control equation:

$$W(t) = K_c \left[T + T_D \frac{dT}{dt} + \frac{1}{T_I} \int_0^t T\, dt \right]$$

For a step change of 10° R, in feed temperatures, a "best" set of constants was found by trial and error, considering both the integral error squared and the final offset. This set was $K_c = 800$, $T_D = 0.1$, and $T_I = 0.1$. The response of the conventional control system using these constants was almost identical to that shown in Figure 2, for the Lyapunov controlled system. For an initial offset 0.01 in state concentration variables and 10°R, in reactor temperature, a radically different "best" set of constants was found — $K_C = 3200$, $T_D = 0.1$, $T_I = 1000$; and again the response with conventional control was the same as that for Lyapunov control, as shown in Figure 3.

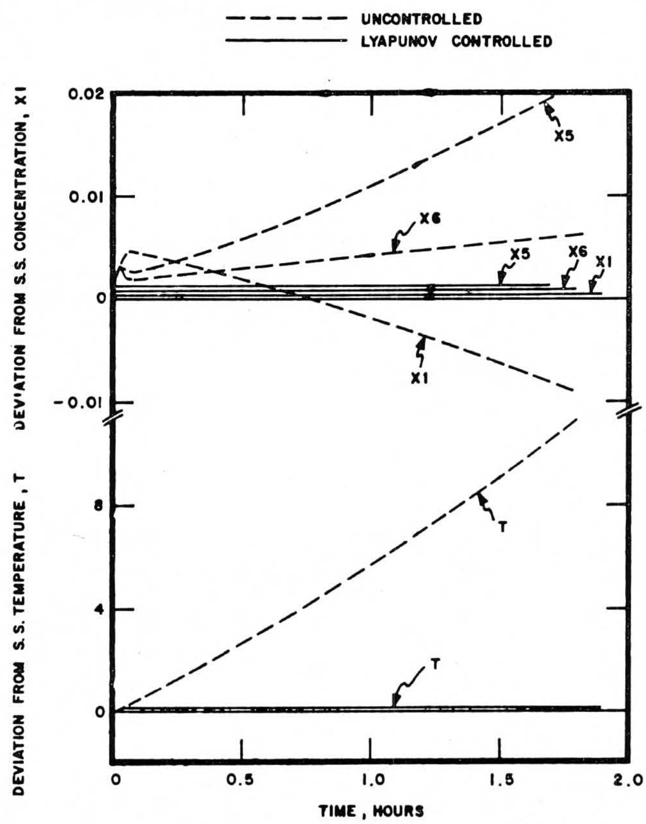

Fig. 4.—Response to a Step Change in Inlet Feed and Recycle Temperatures and Recycle Composition.

It appears that conventional control does almost as good as Lyapunov control when the controller constants are set at the "best" set for a particular type of upset. But this cannot often be done. Figure 5 gives the response of a conventional controller to a step in feed temperatures, with the constants set for the initial offset case. Control here is not as good as that shown in Figure 2, the comparable Lyapunov case. The discrepancy is even greater when the best tem-

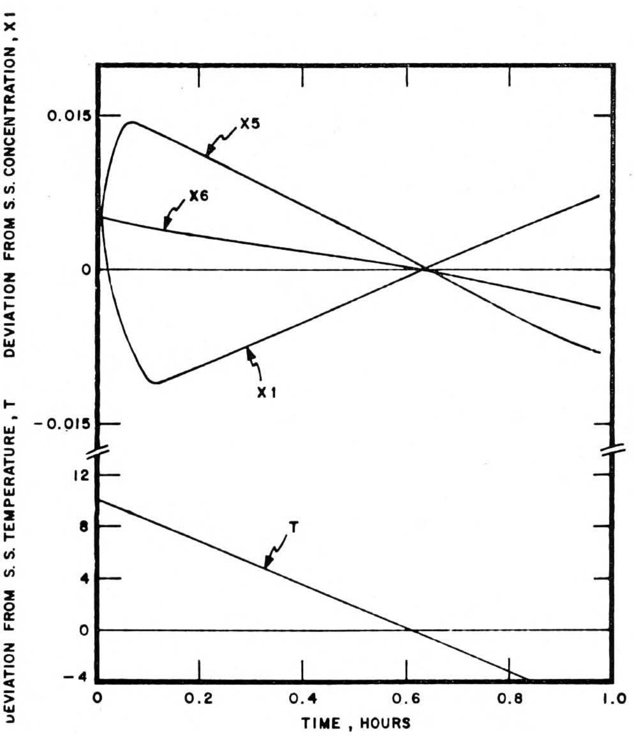

Fig. 5.—Response to a Step Change of 10°R in the Three Feed Streams with a Conventional Three-Mode Controller.

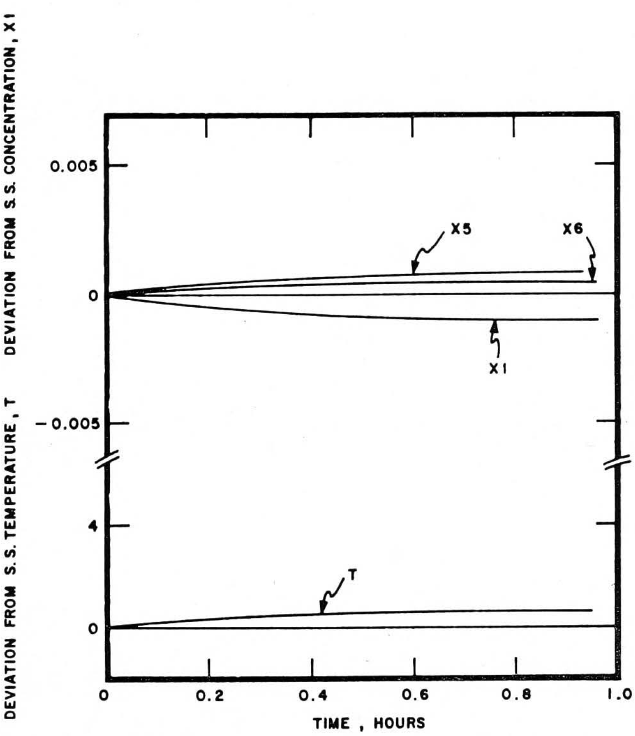

Fig. 6.—Response to an Initial Offset in Reactor Temperature and Concentration with Conventional Three-Mode Controller.

perature step constants are used to control initial offset. Figure 6 shows the results of such a test, in which the response is completely unstable, rather than stable as in Figure 3, the comparable Lyapunov case. The Lyapunov method operates equally well for both types of upsets, which is not true of conventional control.

CONCLUSIONS

Dynamic optimization has been shown to be possible utilizing a method related to the Lyapunov stability criterion. The method, as presented, is simple and relatively easy to apply. It seems to work well in control of a reactor system which is unstable without control. Additional work is necessary, and is currently being carried out, to firm up the mathematical justification for the procedure followed. So far, it works well for cases studied, and requires a minimum of calculation, so it is a reasonable approach to follow. Extension to other systems can follow directly from the example of this paper since the dimension of the state vector does not appear to be a limiting factor.

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Dr. William F. Stevens received his undergraduate education at Northwestern University, graduating in 1944. After 2½ years as a radar officer in the U. S. Naval Reserve, he continued his professional education at the University of Wisconsin, being awarded the Ph.D. in 1949. He then spent two years as a research chemical engineer with the B. F. Goodrich Company. He joined the faculty of the Chemical Engineering Department at Northwestern University in 1951, and has been there continuously since that time, being appointed Professor in 1964. He has published over 35 technical papers, primarily in the area of process control and process optimization. Recently he has spent a portion of his time in administrative activities as Associate Dean of the Northwestern University Graduate School.

Chemistry

Makes The

Chemical Engineer

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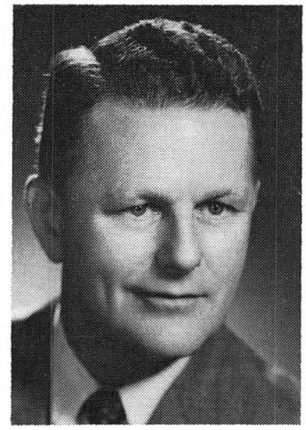

The chemical engineer is characterized by his versatility—his ability to apply a varied training to problems as they relate to research, development, works engineering, manufacturing and sales. The recognition and solution of these problems require that the engineer have, among other qualities, a knowledge, understanding, and an ability to communicate his thoughts on the relationship that exists between the chemical and engineering aspects of a problem.

The practicing chemical engineer relies heavily on organic and physical chemistry—to a much lesser degree on qualitative and quantitative analysis—in his varied technical activities.

There are many ways in which a chemical engineer can be characterized, but among his many attributes his versatility is outstanding.

This is as it should be because the problems and opportunities which confront the practicing chemical engineer demand that the individual be adaptable and reach out to almost any discipline in his search for the best solution to a problem.

In evaluation of the chemical engineer in industry, judgments have been passed on the kinds of technical training and proficiency that are required to contribute effectively. Opinions have been expressed that sales and manufacturing require an individual with certain technical training, strengths and interests in contrast to that required for research and development. In practice the individuals who are concerned with problems in all the areas must have sound technical training to achieve above-average performance. The basic difference between the jobs can be related to how the technical training is applied, personal interests and qualities of the individual.

Chemistry plays a basic role in the development of the engineer. It is vital to the solution of problems in all areas with which chemical engineers are concerned. The difference occurs in how basic chemistry is used or applied to the solution of problems.

The chemical engineer who is concerned with *R & D* activities must have a good *knowledge of chemistry* and he must be able to *use* that knowledge to solve research problems. These may be related to process analysis, the planning of experiments, design of laboratory apparatus, interpretation of results, development of basic data, design of pilot plant equipment, etc. The knowledge and ability to use chemistry is basic to the effective solution of chemical engineering problems in a research or in a development assignment.

The chemical engineer who is concerned with the *design* of process equipment or is responsible for plant design must have an *understanding* of all phases of chemistry and he must have the ability to interpret this understanding in his design.

The research engineer is generally concerned with the study of reaction systems. The basic data that are developed completely describe and qualify the features that must be recognized to satisfy the process. The design engineer must extend his understanding of the chemistry to interpret the basic data in the form of a workable reactor.

The Chemical Engineer who is concerned with the design of process equipment or is responsible for plant design must have an understanding of all phases of chemistry and he must have the ability to interpret this understanding in his design.

The design engineer is frequently committed to take a greater responsibility for separation and auxiliary equipment. Without a knowledge and understanding of chemistry and physical chemistry the design engineer will not be in a position to evaluate the basic data and the requirements and limitations that the chemistry may impose on the design of the equipment and plant.

The chemical engineer who is concerned with *manufacturing* must have an *understanding* of chemistry and he must be able to apply that understanding to analyze problems to achieve effective control of his operation. The modern manufacturing supervisor is much more than an administrator. He must have an ability to apply an understanding of chemistry to control his operation, diagnose difficulties, and recognize the opportunities for technical improvements. He must be able to intelligently and clearly present a problem proposal to a chemist and have sufficient knowledge to interpret a recommendation for a correction or an improvement.

The chemical engineer who is concerned with *sales* must have a good *understanding* of chemistry to *communicate* information about the chemical properties of his company's product. He must be able to understand and communicate the customers' technical problems and needs to his company's technical center. The sales engineer today is much more than a peddler or an individual who takes orders. He may be a trained, experienced chemical engineer who knows his product and is sensitive to his customer's problems and needs.

His technical strength is such that in many cases he can solve chemical and engineering problems for the customer on the spot, and he can participate in an intelligent discussion of technical needs to present an analysis for his company that identifies product deficiencies and requirements. In many cases he may suggest either an approach, a program, or possibly a solution to the problem.

In order to understand how a chemical engineer uses his knowledge of chemistry to enhance his professional development we should examine the manner in which he gains experience in industry.

The new graduate possesses a strong technical appetite and he demands that his first assignment take maximum advantage of his training in the engineering discipline. In general then, the new hire is assigned to a research and development activity. As the individual gains experience he identifies interests and personal qualities which, when superimposed on his basic technical strengths, can provide him with a higher degree of personal and professional achievement than he can realize as a career engineer. He then may pursue a career in administration or continue his professional development in sales, manufacturing, research, development, etc. It is well to emphasize again that the extension of his career is based on his reinforced technical training, personal qualities and interests; but underlying all of these directions into which his career may extend is the basic need for a working and communicating knowledge of chemistry.

In the discussions which we have held with individuals who are actively engaged in the areas that have just been discussed, it was generally agreed that the following needs for chemistry exist:

General—a thorough knowledge of chemical reaction principles and mechanisms, particularly in organic chemistry.

Chemistry—A knowledge of chemistry (organic and inorganic) is vital to a chemical engineer to ensure his ability to solve problems, to design facilities and to communicate with his colleagues, the chemists and the customer.

Physical Chemistry—for the engineer perhaps the most important branch of chemistry. When combined with the derivatives of mechanics, i.e., mass and energy transport, it can serve as a foundation for the solution of most problems that may concern a chemical engineer.

Qualitative and Quantitative Chemistry—Benefit may be derived from the manipulative skills which are developed. It is felt that this training can be achieved in a shorter time and the information should be presented in a survey course.

Chemical engineers should be exposed to some aspects of analytical chemistry and should be familiar with instrumental methods that can be used for raw material, process streams, and product analysis.

The modern chemical engineer must have a practical knowledge of all phases of chemistry, regardless of his field of interest. The curriculum should place greater emphasis on organic and physical chemistry and less stress on qualitative and quantitative analysis.

Mr. Thaddeus W. Tomkowit is general superintendent of the Process Department at the Chambers Works of the duPont Company, Deepwater, N.J. He received the Ch E degree in Chemical Engineering from Columbia University in 1942 and has experience in research, development, engineering, and manufacturing with the duPont Company. He is past national chairman of AIChE Student Chapters Committee and presently is a national director of AIChE.

ChE news

Readers and others are invited to submit news items and technical announcements of professional interest for publication here. Consideration must be given to the fact that CEE publishes quarterly.

STILLWATER, Okla.—The second annual educational conference on process design will be held on the campus of Oklahoma State University here March 4 and 5. The lectures at this conference will be on the design of process reactors.

Sponsored by the School of Chemical Engineering, the two-day meet will feature lecturers with academic and industrial backgrounds, according to Prof. Wayne C. Edmister, conference director.

In addition to general considerations in reactor design and analysis, subjects to be covered include gas-liquid and gas-solid non-catalytic reactors, mathematical modeling of reaction rate data and chemical reactors, reactor and regenerator analysis and design, and control and optimization applications.

Lecturers for the conference are Prof. J. J. Carberry, Department of Chemical Engineering, University of Notre Dame, Notre Dame, Ind.; Dr. J. R. Kittrell, Chevron Research Corp., Richmond, Calif.; and Dr. V. W. Weekman, Jr., Mobil Research and Development Corp., Paulsboro, New Jersey.

Information regarding technical content of the conference is available from Prof. W. C. Edmister. Housing and registration forms are available from Dr. Monroe W. Kriegel, director, Engineering and Industrial Extension, Oklahoma State University, Stillwater, Okla. 74074.

ChE views and opinions

On what sort of place, if any, THEORETICAL AND MATHEMATICAL studies should have in graduate CHEMICAL ENGINEERING RESEARCH*

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Four questions on the suitability of mathematical studies are raised; namely, whether they have a place as training, whether they are practical, whether their methods are suitable and what is the role of rigour.

Question: On what sort of place, if any, theoretical and mathematical studies should have in graduate chemical engineering research.

In order to contain our subject within reasonable bounds we propose to treat it under four points of inquiry:

I. whether mathematical studies have any place in the chemical engineer's training;

II. whether mathematical and theoretical studies are practical or contemplative;

III. whether the methods of mathematical and theoretical studies are conformable to those of engineering;

IV. whether mathematical rigor is a notion from which the engineer may profitably be dispensed.

ARTICLE I.

Have mathematical studies any place in the chemical engineer's training?

1. It would seem that mathematical studies have no place in the training of a chemical engineer whose true nature is fulfilled in making and doing things. Now the end of mathematics is not to do or make anything. Therefore mathematical studies are alien to the engineer's training.

2. Moreover, there are more important subjects in the engineering curriculum, which is already a full and difficult one. Therefore mathematics should have little part in the curriculum.

3. Again, the training of the engineer should be directed towards developing those faculties that he will need in industry. The principal faculty of an engineer is to make responsible judgments and correct decisions on the basis of information which is always incomplete and often faulty. Now there is no analogous situation in mathematics and therefore it adds nothing to the engineer's training.

On the other hand, mathematics is where the art of generalization is best seen and learned and where the formal object of any science is best displayed. Simple examples free from the compounded difficulties of the material objects of chemical engineering are often didactically desirable.

REPLY

1. Even if the formal object of mathematics is not to make any material thing it is nevertheless often the efficient cause of a good design. Moreover the engineer takes pride in doing for a penny what any fool may do for a dollar. Now if each problem must be considered *de novo* as it arises without the generalizing power of mathematics he is certainly not practicing the economy of which he is so rightly proud. Fur-

*Presented at the Annual Meeting of ASEE, June 19-22, 1967.

ther it may be questioned whether mathematical studies are so ineffective for does not the poet write[1]

We are the music makers,
We are the dreamers of dreams,
Wandering by lone sea-breakers,
And sitting by desolate streams;
World-losers and world-forsakers,
On whom the pale moon gleams:
Yet we are the movers and shakers
Of the world for ever, it seems.

2. To the second objection we may reply by asking what constitutes a more important subject. Certainly mathematics must take its place along with chemistry, physics and engineering science in competition for the student's attention and not arrogate to itself a primacy which in this context it does not possess. But it may be argued where, if not at the university, has the opportunity to become acquainted with both the utility of the methods and beauty of the notions of modern mathematics; as the poet[2] says, *'Omne tulit punctum qui miscuit utile dulci.'*[2]

3. Though it be true that the engineer's task is to make decisions on the basis of incomplete information, yet he can gain part of the experience on which this ability is founded by the study of mathematical models. For example, the formal nature of an exothermic reaction is to possess at each composition a temperature at which the reaction rate is greatest, which temperature is somewhat lower than the equilibrium temperature for the same composition. And this may be learned, not only by experience with the material objects of chemical engineering, namely reacting chemicals and reactors, but more generally from experience with the formal objects of kinetics, namely the kinds of reaction rate expression that are found to be useful. The engineer may thus supplement his incomplete information on a particular reaction by an understanding of the general behavior of a whole class of reactions.

ARTICLE II.

Are mathematical studies practical or contemplative?

1. It would seem that mathematical studies are not part of any practical science, for Aristotle says "a practical science is that which ends in action."[3] Now mathematics is one of the formal sciences whose truth depends on their internal consistency and not upon any relation to the observable world as is the case with the factual sciences.

2. In the hierarchy of the sciences the factual sciences occupy an intermediate position between the formal and the applied. Now engineering is clearly an applied science and practical, therefore mathematics is far removed from it and wholly contemplative.

On the other hand it is generally acknowledged that the purist attitude of such eminent mathematicians as the late G. H. Hardy (who, in his *Mathematician's Apology,*[4] crowns the theory of numbers as queen of the mathematical sciences because of its [her] complete uselessness) is an extreme one. Mathematical thought is diverse in its ramifications and penetrates to other disciplines.

REPLY

1. Nothing is more practical than a good theory, for to be good it must have clear indication within itself of how it may be proved, i.e., tested. Again, theory comes before experiment since some vision is needed to correctly formulate any experiment. Therefore theoretical studies are of practical value.

2. Moreover, although the division of sciences into formal, factual and applied is a useful one, it would be a mistake to interpret it rigidly and refuse to recognize the interpenetration of ideas throughout them. For though applications of such a subject as number theory are rare, this does not mean that they may not be found nor will the theory be defiled if they are.

ARTICLE III.

Are the methods of mathematics conformable to those of engineering?

1. It would seem that the methods of the mathematician have little or nothing in common with those of the engineer. For mathematics is an axiomatic science proceeding by strict deduction, and engineering lore is founded on direct experience and proceeds by trial and error.

2. Again the technique of the chemical engineer is to scale up his apparatus by stages, and wisely so for he deals with processes that are rarely understood in any complete sense. This procession of scales has no part in mathematics.

3. Moreover, the mathematical approach will often start with so drastic an idealization as to

Better soap may be made, but better living is not attained if cleanliness has become the first rather than the second virtue.

take it one remove from engineering realities at the outset.

On the other hand, rational thought must permeate all purposeful human activity, including that of the chemical engineer. Now rational thought is to be seen par excellence in mathematics and so learned there.

REPLY

1. It is false to assume that, because the ultimate presentation of mathematical results is deductive, the context of discovery is also purely deductive. In fact mathematics requires as much imagination as it does logic, and proceeds by the pattern of conjecture and confirmation or refutation familiar in all sciences. Moreover it has its own experiences of theory building which are just as valuable to the engineer as the more banausic experiences of plant building.

2. Even though scale-up has no direct counterpart in mathematical theory it is served by the notions of dimensional analysis. The correlations of empirical data by means of dimensionless groups need to be informed by a proper understanding of the underlying equations or most spurious results can be generated (cf. P. N. Rowe's illustration[5]). Although we are still some distance from completely a priori design of chemical reactors, the progress of scaling up is now often greatly expedited by proper mathematical modelling at an early stage.

3. Furthermore, though a problem is often idealized considerably when formulated in mathematical terms, this does not necessarily take it completely out of touch with reality. There is a hierarchic and iterative aspect to idealization. A situation may be grossly oversimplified at first and yet its analysis can form the basis for an interconnected set of problems in which more complete solution is built up by successively including more refinements and evaluating their effects.

ARTICLE IV

Cannot the engineer be dispensed from the notion and habit of mathematical rigor?

1. The mathematician's notions of rigor would seem to be wholly out of place in the context of engineering applications. For rigor implies exactitude and we have admitted that a mathematical model is always an idealization and its exactitude is therefore an artifact of analysis and does not belong to the real world.

2. Moreover in any model the constants and parameters will be imperfectly determined. It seems therefore foolish for the engineer to worry about existence theorems, strict deduction, necessity and sufficiency and the like, when his basic quantities are always open to error.

3. With the power of modern computers numerical solutions can often be obtained faster than any general properties of the solution can be rigorously proved and a numerical answer is what the engineer wants. On the contrary, "In physical theory, mathematical rigor is of the essence" (so Truesdell[6]).

REPLY

1. If a mathematical model of a real situation is constructed, its utility will be judged by the conformability of its consequences to what may be observed. Now if these consequences have not been rigorously deduced, a comparison between them and observations that may be made is devoid of meaning and has nothing to say to the validity of the model. The whole endeavor of theoretical analysis is thereby rendered futile and this because it is not true to itself. For though the notion of rigor exists only formally in the mind, it exists fundamentally in an instance of mathematical analysis. A sloppy analysis is therefore not 'a good enough approximation for engineering purposes'; it is a deformed creature that has repudiated its own essence. This does not mean that it is always possible for a given person, or even any person, to provide a full, complete and rigorous demonstration of all propositions. But this failing must be honestly recognized as a fault, which may be corrected later by the person himself or by someone more able than he. It is only a snare when it is overlooked. When it is derisively ignored it is not only a snare but a corruption.

2. What we have said above sufficiently answers the second objection, but it may further be pointed out that a proper mathematical analysis can evaluate the effect of the errors that there will be in the estimation of constants. It can also suggest ways in which these constants may be determined more accurately and prescribe confidence limits for them.

3. Nowhere is the need for rigorous mathematical theory better seen than in the present day use of the computer. Without an existence theorem there is no assurance that the numbers ground out by the numerical solution of an equation have any meaning. There may be some intuitive presumption of their meaningfulness but let this be honestly recognized. The particular virtues of the digital computer are its speed, "careful attention" and "indefatigable assiduity"[7]. These may be exploited, but they need also to be controlled by a rationality which is too easily sacrificed in a culture which appreciates it so superficially. It is seldom wise and never desirable to start computing before obtaining a good qualitative feel for the form of a solution; the ability to do this is one of the fruits of mathematical training.

We therefore conclude that there is a valid place for theoretical and mathematical studies in chemical engineering research, provided that their virtues and limitations are properly understood and held in balance. When unwarranted claims or unnecessary derogations are made from either direction, then the whole temper and spirit of natural philosophy is vitiated. Better soap may be made, but better living is not attained if cleanliness has become the first rather than the second virtue.

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Dr. Rutherford Aris was born in England in 1929, studied mathematics in the University of Edinburgh and taught it to engineers there. He has degrees from the University of London (B.Sc. (Math); Ph.D. (Math. and Chem. E.); D.Sc.). He worked a total of seven years in industry, but since 1958 he has been in the Chemical Engineering Department at the University of Minnesota enjoying the liveliness of its interests, both technical and cultural, and endeavouring to contribute to this vitality and communicate it to his students.

Summer School for Teachers of Chemical Engineering which was held at Michigan State University last June. For that reason, we have on hand a certain amount of material that will be published during the year. But we would also like to include in each issue one or two articles on chemical engineering education that have been submitted to us by people in the universities and in industry. Accordingly, your contributions are definitely solicited.

CHEMICAL ENGINEERING EDUCATION wishes to provide something of interest to the entire profession: educators in the university and engineers in industry; the large graduate-oriented departments and those with small undergraduate programs; the theoretically-inclined and the practice-oriented; chemical engineering professors and chemical engineering students. But while we serve all, we do not intend to avoid controversy nor will we shirk our responsibility to speak out editorially on matters we feel are of importance to the profession. We hope our readers will do us the favor of writing when they do not agree or also when they **do** agree with something they have read in **CHEMICAL ENGINEERING EDUCATION.** In later issues we intend to publish letters as well as articles that set forth differing views on important topics. We are always interested in your ideas as to how we can make **CHEMICAL ENGINEERING EDUCATION** a better journal. With your continued help and support we can provide an important and needed service to both the teaching and the engineering professions, to our students, and to our society as a whole.

Ray Fahien

*Are engineers selling their birthright for a place in the ivory tower?**

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When I graduated from college, now nearly forty years ago, engineering was defined rather simply as "the art of utilizing the knowledge of the sciences in the production of machines and materials for the benefit of mankind". There was also included some reference to the fact that engineering was to be accomplished for a profit. Science was defined as "an organized body of knowledge." I don't recall any definition of the word "art," but I would suggest that the word art refers to the "doing" and science refers to the "knowledge" used in the "doing." Perhaps skill would be a better word.

In any field of endeavor, both skill and knowledge are required. Even the scientist, engaged in pure research, must have some basic skills. At the very minimum, he must be able to present the results of his work to others in a satisfactory manner. On the other hand, the artist, engaged in abstract art, must have some basic knowledge of the materials and techniques necessary for accomplishment of his work.

In recent years, there has been a tremendous growth in the accumulation of knowledge. As a result, there has been a steady upgrading of the term "science." This is called the "Scientific Age" and the "Scientist," once considered a peculiar individual working in the mysterious confines of something called a laboratory, has now become a well-known and highly respected individual. No one can regret this development. Public recognition of the valuable work of the scientist has been long overdue. However, there are some side effects of this trend that are not so desirable. While respect for knowledge has been increasing, respect for the skills necessary to put this knowledge to use has been steadily declining. For example, when a space ship has been put into orbit successfully, it is hailed as a great "scientific" achievement. When there is a failure, it is referred to as an "engineering" failure, or perhaps less painfully, as a "technical" failure. The terms "engineering" and the title, "engineer," are being definitely and rapidly downgraded.

It is disappointing to note that even among the members of our own profession, there is a reluctance to use the title "engineer." *In reviewing the biographical sketches of recent candidates for offices of one professional society, it was noted that not a single candidate referred to himself as an engineer.* The most commonly used titles were Executive, Administrator, and Educator. (No one, however, referred to himself as a "teacher".)

Engineering, as a profession, and engineers, as individuals, have been known and respected, primarily for their accomplishments; i.e., the actual production of materials and machines. Today there seems to be a growing tendency to believe that engineers should be respected for their knowledge and not for their accomplishments.

A number of years ago, a young engineer of my acquaintance, was proud of the experience he was getting in heat exchanger design. He pointed out that he had "designed" nine heat exchangers that week. "How many of your heat exchangers have been built?" I asked. "Oh, none of them have been built, but what has that got to do with it? I still have the design experience." Actually, of course, he had experience in applied mathematics—not heat exchanger design.

At a more recent technical meeting, I heard

*Presented at the Annual Meeting of ASEE, June 19-22, 1967.

If engineering as a profession, and engineers as individuals, are to retain a prestige based on accomplishment, then there must be a reversal of the present trend to confine engineering to design and management offices.

a discussion on heat exchanger design that went something like this: "There are about 128 variables that affect heat exchanger design. Of these, all but about 32 can be considered to be of negligible importance. With the 32 variables, we could design the ideal heat exchanger. It would require about $15,000 worth of computer time for each exchanger and my company objects to this. I know that these exchangers sell for about $3000 and there would be a net loss of $12,000 on each exchanger, but think of the valuable information we would get." Unhappily, for the "engineer", the company he works for sells heat exchangers for a profit, not "valuable information."

In a conference on a recent plant design, I asked the design engineer if he felt that the resulting plant would be "operable." "What do you mean?" he asked, with a perplexed expression. "Well, can the operating engineers operate this plant satisfactorily?" He was astonished. "I couldn't care less!" was his reply. "This design is based on methods established in the technical literature. I have checked my mathematical computations and there are no errors. If it does not operate satisfactorily, this is of no concern to me."

I submit that the attitudes reflected above do no good to the engineering profession and are not the proper attitudes for an engineer.

The rapid expansion of the sciences in recent years does create difficult problems in the education and training of chemical engineers. It has seemed to me that the chemical engineer has always been somewhat more fortunate than his colleagues in mechanical and electrical engineering, since he has had the additional training in chemistry as well as the basic mathematics and physics. Now, the expansion in physics and mathematics places an additional burden on the chemical engineering student. In addition to this, the present recommendations that 20% of the students' time be devoted to the humanities, adds still another burden.

I would suggest that the whole humanities requirement be eliminated. In reviewing the catalogue of one midwestern university, I noted their requirement for credit for a course in the humanities. "The course must be one that adds to the student's knowledge in a given field, but not to his skill." For example, he may take a course about the theater, but he may not take a course that is designed to develop his skill as an actor. He may take a course about music, but not a course that is designed to teach him to play a musical instrument.

It is inevitable that time spent in the laboratory courses has been, and will be, reduced. In my college years, we were required to take courses in forging and heat treating of metals and also a course in pattern making—laboratory courses taken during the summer months. I still have a set of wrenches that I laboriously forged during that summer. Unfortunately, I have never found a bolt head or nut that they would fit. The case hardening was excellent and I cannot grind them down to fit anything, but they are nice wrenches.

We also had some sixteen clock hours per week of quantitative analysis each semester during the second year. I do not recommend that we return to this; however I do believe that we have reduced that part of the curriculum that can be defined as "training," as opposed to "education," to beyond tolerable limits. Recently, the dean of one engineering school asked me, quite seriously, if the courses in chemistry could not be eliminated from the curriculum in chemical engineering. "I know it sounds silly," he said, "but with the addition we have to make to the curriculum, we simply do not have time to provide the laboratory hours required."

One area in which I believe that laboratory work has been reduced beyond tolerable limits, is in engineering drawing. Many young engineers not only cannot produce a satisfactory drawing, often they cannot read one.

Some colleges have attempted to meet this problem by adding a fifth year to the course of study required for the B.Ch.E. degree. This has resulted in a drop in enrollment and to offset this, they have worked out a combined curriculum that would award the student an additional degree in Business Administration. I do not believe that a student can be given adequate training in both disciplines to justify this program. He is either a Chemical Engineer with a minor in Business Administration, or he is a graduate in Business Administration with a minor in Chemical Engineering.

I am aware of the fact that a number of the larger chemical companies subscribe to the theory that chemical engineering curriculum should be heavily weighted with courses in the sciences. They say, "You give them all the mathematics, chemistry, physics, etc., that you can. We will teach them the necessary engineering after they come to work for us." Such a procedure does an injustice to the student who expects to be trained in principles of engineering. It also puts the student who elects to work for the smaller companies, at a disadvantage.

When I returned to teaching after some years in industrial work, I introduced a new course in plant design. The course was not intended to develop proficiency in process calculation, it was designed to acquaint the student with the myriad problems which arise from the very beginning of a project. It included site selection, literature survey for necessary data and estimating methods for both equipment size and cost. The course was given in the last half of the senior year. About midway through the course, one student came to me with this comment: "I came here to become an engineer, although I had not decided on which field of engineering. I selected chemical engineering because I met another freshman that I liked and he was going to take chemical engineering. For three and a half years, I have been taking courses in Chemistry, Mathematics, Physics, English, etc., but I never knew just what chemical engineers did until I started this course."

This course was very popular with the students. Actually, it could be given in the last half of the second year or first half of the third year. If the student had some idea of the problems of chemical engineering, at an early point in his training, he would have a better understanding of the requirements for process design and unit operation courses which would follow.

There is a growing concern among some engineering companies for the increasing difficulty they are experiencing in getting new plants "on stream." As a vice president of one engineering company put it, "We design and build a new facility and then send out a 35-year-old "hot shot" to operate it. Then we find out that he simply cannot do it."

If the present trend toward higher academic achievement for the professional engineer continues, there will be an unavoidable gap between the engineer and the supervision of engineering at the working level.

Having had some experience in operations, it is my opinion that almost all difficulties in operating a plant stem from lack of basic engineering knowledge. Actually, I might say, from lack of mechanical and electrical "know-how." For example, while inspecting a pilot plant installation, I pointed out to the project engineer that his pumps had not been properly grouted in. He was highly indignant. "We consider grouting to be window dressing and we do not waste money on this kind of thing." He was wasting money, however, on constant piping repair and packing problems, although the size of the operation was such that it was not too important. The point is, that this was the hallmark of a careless workman and he had a Ph.D. in chemical engineering from one of the leading colleges.

When I was a student, we had an "Engineer's Day" each year, when we dressed up the laboratories for a public inspection. I think that the good Dr. James R. Withrow, in one of his humorous moods, was responsible for one exhibit. Along one wall of the laboratory was a display of such equipment as specific gravity spindles, viscosimeters, analytical balances, etc. The title card read, "Proficiency in the use of this equipment required of all candidates for the B.Ch.E. degree." The next exhibit was a table containing pipe wrenches, chisels, hammers, etc., along with a card stating, "Proficiency in the use of this equipment required of all candidates for the M.Sc. degree. The last exhibit consisted simply of a wheelbarrow and shovel, along with the sign, "Proficiency in the use of this equipment required of all candidates for the Ph.D. in Chemical Engineering". At the time, I thought this simply a macabre jest, but as the years have gone by, I have learned to appreciate the wisdom displayed in this exhibit.

If engineering as a profession, and engineers as individuals, are to retain a prestige based on accomplishment, then there must be a reversal of the present trend to confine engineering to design and management offices. Engineers must be willing and encouraged to go "where the action is." There is a prevalent tendency, even within the profession, to downgrade the work of the engineer in the field. The "hard hat and leather booted" engineer is often referred to with some trace of contempt by his colleagues at the design level. Nevertheless, it is the field engineer who is called upon to correct design errors during the construction, and when a plant goes on stream easily, it is largely due to the efforts of the "hard hat and leather boot" engineers. It is, in fact, a common practice to revise drawings after construction to get an "as built" design.

If we wish to continue to promote engineering as the profession which practices "the art of utilizing the sciences in the production of machines and materials for the benefit of mankind," then I would like to make the following suggestions:

1. Re-evaluate our engineering curriculum with the goal of restoring to it the basic engineering courses. Much of the new material added to the curriculum as new courses, could be incorporated into existing courses.

2. Take a second look at the requirement that 20% of the engineering curriculum be devoted to the humanities.

If we do not wish to continue with the image of the engineer as the man known for his accomplishments, then we should accept the fact that the present trend is leading the engineering profession into a field of activity, not directly connected with what has been traditionally the domain of the engineer. *In the normal course of this development, engineering will become a branch of science.* There is already an increasing use of the term "engineering science." I asume that the term refers to what was once called applied science. It will also lead into what may be called applied mathematics.

Some well-trained technicians are already pushing the engineer out of contact with actual construction and production. Their argument is that because of the professional engineer's broader knowledge of the field, he should confine his talents to those of overall management. What they are implying is that because of the time spent in broadening his knowledge, he is no longer sufficiently well acquainted with the details of the work to provide adequate supervision at the working level. There is considerable merit to this point of view.

Assuming that the present trend toward higher academic achievement for the professional engineer will continue, then there will be an unavoidable gap between the engineer and the supervision of engineering at the working level. Schools offering technical training are rapidly upgrading their courses and it is possible that such schools will, in the future, be called on to provide engineering technicians adequately trained to supervise the work previously supervised by engineers.

My personal preference, for a number of reasons, would be to return to the professional institutions the concept of practical application of the knowledge of the sciences to the field of engineering.

Professor Ralph H. Wing is a graduate of Ohio State University. His early teaching experience was at Pratt Institute, Brooklyn, N.Y. Recent teaching experience was at the West Virginia Institute of Technology where he was head of the department of Chemical Engineering. His engineering experience includes work with M.W. Kellogg Co. and Ford, Bacon and Davis, of New York and the Research and Engineering Division of the U.S. Army Chemical Corps. His operating experience includes work with Heyden Chemical Corps. at Danville, Pa. and Fords, N.J. and Dodge and Olcott at Bayonne, N.J. He is the author of a number of papers dealing principally with plant operating problems.

Readers and others are invited to submit reviews of books of interest to the profession. Teachers are especially encouraged to write reviews of current textbooks they have tested in the classroom.

Non-Newtonian Flow and Heat Transfer
A.H.P. Skelland
John Wiley and Sons, New York (1967)
pp. vii + 469, 112 illustrations, $17.95

Many fluids involved in todays processing are non-Newtonian. For this area of study, Professor Skelland has provided the student engineer and the practicing engineer a text that is both detailed and lucid. To accomplish this he has excluded much of the mathematically complex and often obscure developments of rheology, and has included a wealth of practical examples. For the teaching of engineering methods and to the practicing engineer, who because of his age and the newness of the field managed to escape a depth of treatment, this book can be recommended. It was not written with the intent of being a text for advanced graduate research orientated courses, for these there are several books available; e.g. Frederickson, Lodge, or Brodkey.

A breakdown of the coverage is of interest. After introductory sections on classification of fluid behavior and experimental determination of flow properties, the author deals with the mechanics of steady flow in tubes; of this, about one third is on turbulent flow. Steady flow in annuli, parallel plates, and rectangular ducts are all briefly treated. The remaining half of the book covers optimization of non-Newtonian pipe systems, boundary layers, mixing and agitation, and heat transfer. The balance appears to be satisfactory considering the engineering nature of the text and the state of the literature in the field.

There are areas of interest to researchers that Skelland has avoided. Some may criticize him for this, but I feel he has done well to avoid them. With a cutoff time of early 1966 he could not include the very recent ideas on the second normal stress difference and drag reduction. Even today, such topics as these and the relations of viscoelasticity and thioxtropic behavior are still far from completely understood. I fail to see how one could write a universally satisfactory discussion of these factors, let alone how to account for the observed effects in engineering design. Much more work will have to appear in the literature before these topics can be adequately treated in an engineering text.

Finally, I should mention that this review and the feeling expressed herein are based on the use of the text for a quarter course at the advanced undergraduate level and introductory graduate level. The book was used for the undergraduates and master candidates who planned to terminate at these levels. With these, I considered the use of the book totally successful.

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ChE problems for teachers

The following problems were prepared by Professor Octave Levenspiel with the help of Professors Tom Fitzgerald and Ralph Peck all of Illinois Institute of Technology. Attempted solutions are to be sent to Professor Levenspiel at IIT who will choose one solution for publication in the next issue and list the names of others who obtained the right answers. CHEMICAL ENGINEERING EDUCATION encourages readers to send in home problems and examination problems (with solutions, please) to Professor Levenspiel or to the Editor. We are also soliciting questions on subjects of general engineering or scientific interest to be presented to our readers for their solution or discussion.

1. Squeezable but incompressible Bubbles la Rue is happily floating in her kidneyish backyard swimming pool when Alfred the Mean sneaks up and pushes her under. Thermodynamically speaking how does his ungallant action affect her energy and entropy?

2. Find the pressure at the base of a column of water 4000 miles high located at the North Pole. Assume liquid in the pipe is incompressible with a density, $\rho = 1.00$ gm/cm^3.

3. At present there are various opinions in the literature concerning the nature of osmotic pressure and how to treat it. For example in the life sciences it is often talked of in terms of "negative pressures." The references in **Science** *158*, 1210 (1967) will lead you to some of these remarkable papers. Do you want to contribute to the discussions? Imagine what you could do by combining it with the ideal gas law! If you can solve the problem below and come up with a length of pipe not more than 5 miles then you are ready for such interdisciplinary exchanges. But you may have other things to say. Who knows—try the problem.

Problem: When a solvent and a dilute solution are separated by a membrane permeable only to the solvent then the pressure difference needed to maintain equilibrium is given approximately by

$$\Delta p = p_{solution} - p_{solvent} = C_{solute} RT$$

Here Δp is called the osmotic pressure. As an example, for fresh water and sea water (roughly 3.5% solids, mostly NaCl) the osmotic pressure is about 22 atm.

Suppose a long continuous tube filled with fresh water and fitted with an ideal semipermeable membrane at the bottom is lowered deeper and deeper into the ocean. Because salt water is more dense than fresh water a depth will be reached where the pressure difference across the membrane will become 22 atm. (higher on the outside).

If the tube is lowered further the pressure difference will exceed 22 atm. in which case water should flow through the membrane into the pipe and fresh water can be recovered at the surface of the ocean.

Assuming that the densities of fresh and salt water remain at 1.00 and 1.03 gms/cm^3 throughout, how deep into the ocean must the pipe extend so that fresh water can be recovered?

4. Here is a design optimization problem based directly on thermodynamics. Somehow this type of problem rarely pops up in thermodynamics texts.

Problem: A company claims to have developed an ideal semipermeable membrane for the desalinization of sea water. How should we operate a continuous flow pilot plant having just one pump and no turbine so as to minimize the energy requirement to produce fresh water?

5. Sea level air at 80° F and 70% relative humidity passes over a range of mountains about 12,000 ft high.

   a. At what level will clouds form?
   b. What is the temperature of the air passing over the range?
   c. If all condensed moisture is removed as rain before the air descends, what is the temperature and humidity of air at sea level in the lee of the mountain range?

Does this phenomenon explain the type of climate found directly west of the Sierras, the Cascades and Mt. Whitney?

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The large and vigorous body of chemical engineering educators in our universities are generating a valuable literature of techniques and skills in research and teaching, much of which up to now has not had a medium of publication. The Board of Publications of the Chemical Engineering Division of ASEE has ensured the future and growth of this literature in chemical engineering education by enlisting the financial support of interested industrial and educational organizations in the publication of **CHEMICAL ENGINEERING EDUCATION.**

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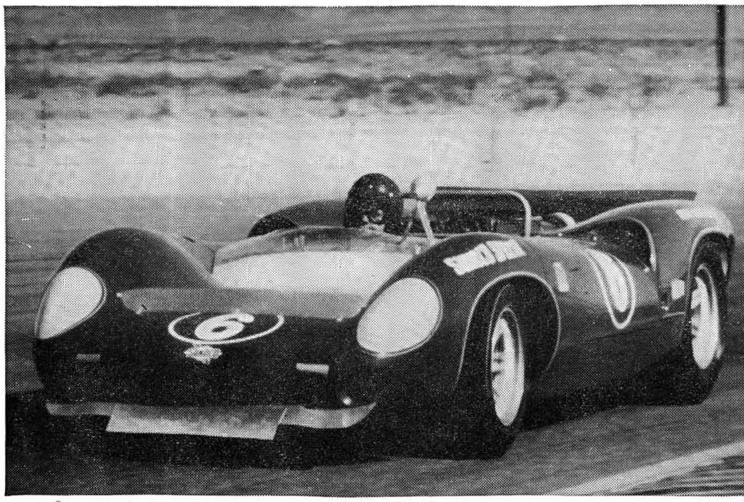
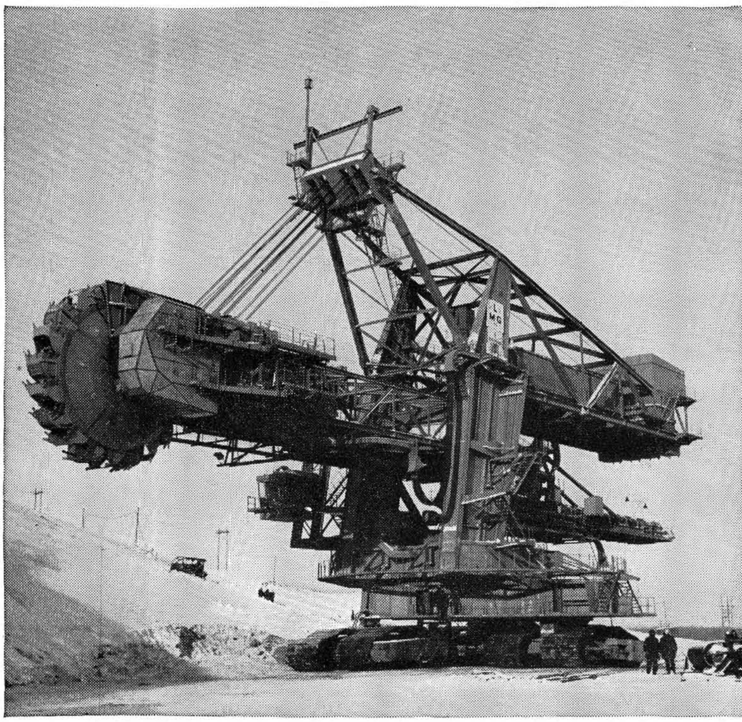
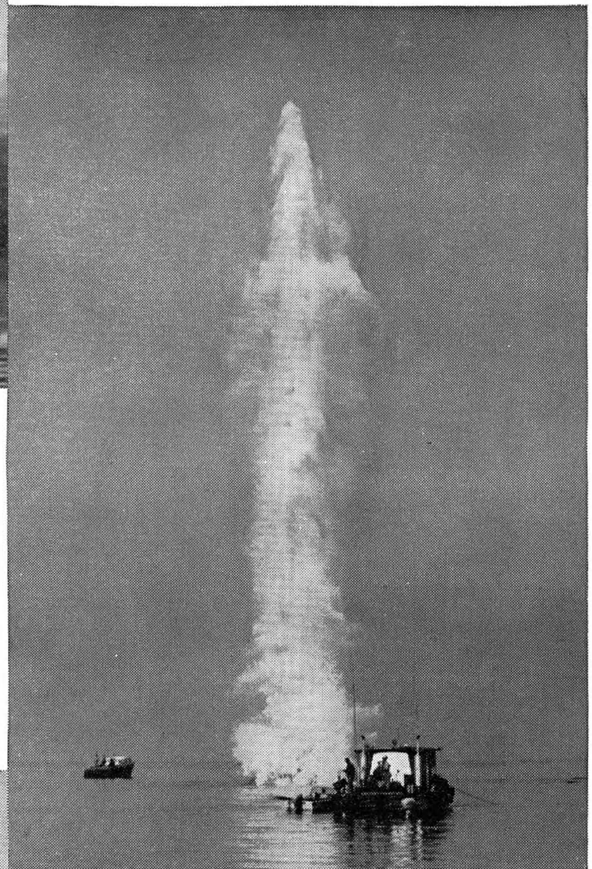


PROVING GROUND. "Sunoco Special" wins 1966 Canadian Grand Prix, Bahamas Cup (Nassau Speed Week), 1967 United States Road Racing Championship, runner-up in 1966 Canadian-American Challenge Cup series. Competition of Sunoco-sponsored cars in major racing events serves as a daring proving ground for Sunoco products.

MONSTER. Giant bucketwheel excavator, earth-eating monster that mines the Athabasca oil sands for Sun Oil's famed Great Canadian Oil Sands Ltd. project in Alberta—a pioneering effort in extending the world's petroleum resources.





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