



chemical engineering education

VOLUME X

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CHEMICAL ENGINEERING DIVISION OF AMERICAN SOCIETY FOR ENGINEERING EDUCATION

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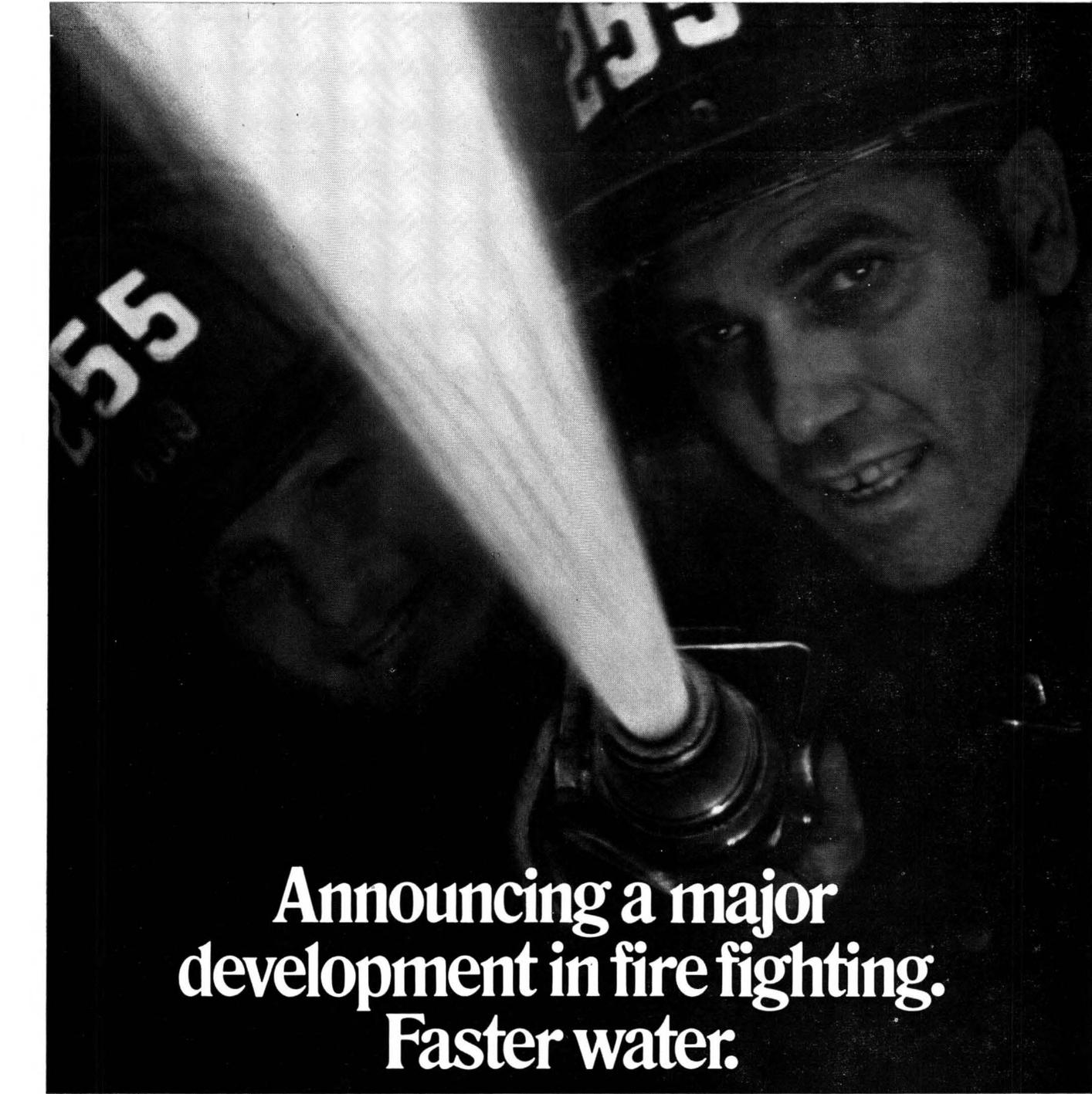
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SOME THOUGHTS ON THE NATURE OF ACADEMIC RESEARCH IN CHEMICAL ENGINEERING

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THIS PAPER HAS GROWN from a request to say something about the scope of chemical engineering research in the universities of North America to the Sixth Interamerican Congress of Chemical Engineering held in Caracas (July 1975). From the beginning it seemed hopeless to attempt a comprehensive descriptive review, for with so vast a cargo it could scarcely hope to make passage between the Scylla of platitudinous dullness and the Charybdis of prejudiced particularity. One might, to be sure, form a matrix with

**The attempt to divorce
teaching and research is fatal
to the life of a university department.**

a row for each university department, a column for each key-word in the chemical engineering thesaurus and elements proportional to the intensity of activity of research on the j^{th} topic in the i^{th} department. Like a famous text on transport phenomena, such a matrix might be read either by rows or by columns, but what would it say? Of quantity, it would speak equivocally; of quality, it would perforce be silent.

Rather than attempting to follow a descriptive path it would seem wiser to ask what kind of research is proper to a university and perhaps even to start on the *via negativa* by noting that purely developmental work is not appropriate to the academy. It is not that this kind of work does not demand great intelligence or resourcefulness—indeed, all the qualities of a good engineer—it is just that it can be done so much better in industry and there it belongs. In saying this I am not in the least denigrating usefulness for chemical engi-

neering has no use for “the mathematician so pure that if you give him a number with a meaning he won’t touch it” [1]. It is rather a matter of the obligations of the worker and the genius of the place in which he does his work. The obligations of the industrial scientist are to the interests of his employer or the needs of his industry and if these obligations cannot be conscientiously met he would naturally seek work elsewhere. The obligations of the academic are to the intrinsic nature of his subject and to the traditions of the learned world—scrupulous analysis, imaginative synthesis and painstaking precision of thought and expression—and if, in fulfilling these, his work is immediately useful he is doubly fortunate. The genius of industry is the spirit of inventive adaptability, that of the academy is the grace of vision and conceptual refinement. Industrial research is, in the language of our day, “goal oriented”, and, whether that goal be a new product or the improvement of an old process, the success of the research is to be measured by the degree of achievement of that goal—by the reliability of the product or the efficiency of the revised process.

A QUESTION OF PROPRIETY

IN MAKING THESE distinctions I do not mean to divide and sunder, nor do I intend to put these several virtues into conflict or opposition. I am not suggesting that all these qualities cannot flourish in one person nor each in the other’s context. Still less am I advocating that they should not interact or claiming that one is a higher road than the other. Such an adversary attitude is unproductive on all counts. It is merely a question of propriety. For the individual worker it is a matter of bent, for “we have only one virginity to lose and where we lost it there our hearts will be.” [2]. It goes without saying that a close contact between industry and university must be maintained for it is of the nature of chemical en-

gineering to find expression in industrial processes and fundamental research must not lose sight of its final cause. It is also well to bear in mind that the cooperation of industry and university may often fruitfully follow a pattern in which the fundamental aspects are taken up by the latter but closely meshed with the questions raised by the development program.

An almost trivial illustration may serve to focus the distinction. In the operation of a continuous fermentor in which two organisms A and B are growing on the same nutrient, it is found that by carefully regulating the flow rate, not one but both populations can be induced to grow together at a healthy rate, whereas at higher or lower feed rates one population tends to grow at the expense of the other until the latter is washed out. In this kind of operation there is some difficulty in maintaining the steady state since the flow rate fluctuates to some degree and considerable skill needed to start up. However it is readily determined that (a) an inoculum of A and B in the correct proportions will lead to a steady growth rate in those proportions, and (b) an increase of flow rate favors A over B and vice versa. This information should be in agreement with common sense and confirmed by a fairly cursory examination of the equations. For practical purposes enough may now be known for satisfactory operation. If this matter were the subject of an academic investigation one would want to go further and, while perhaps growing the bugs in a chemostat for the purposes of some other investigation, one would like to ask a number of further questions: What is the stability of the steady state? Why should the flow rate variation have such an effect on the populations? The growth rates are dependent on the nutrient in a known way, but what are other possible dependencies and what would then be the behavior of the chemostat? Above all one would want to get

It would seem wiser to ask what kind of research is proper to a university and perhaps even to start on the via negativa by noting that purely developmental work is not appropriate to the academy. It is not that this kind of work does not demand great intelligence or resourcefulness . . . it is just that it can be done so much better in industry and there it belongs.

a comprehensive and structural picture to see the inter-relations with other known features of reactor behavior. This desire for comprehensiveness is of course subject to human limitations and short-comings and, sometimes because new techniques have come to light, the work of later authors often repairs the deficiencies of earlier. A study of the behavior of stirred tanks in the early and mid-50's showed the possibility of limit cycles

The obligations of the academic are to the intrinsic nature of his subject and to the traditions of the learned world—scrupulous analysis, imaginative synthesis and painstaking precision of thought and expression—and if, in fulfilling these, his work is immediately useful, he is doubly fortunate.

in their behavior [3]. It was however nearly 20 years before Uppal, Ray and Poore, using revived or new methods, gave a comprehensive picture of conditions under which they could appear [4].

Comprehensiveness is but one aspect of the basic endeavor to understand any subject in which, as always, our "reach should exceed our grasp". It is this fundamental longing after structure which characterises the academic enterprise and from this flow two other characteristics of university research. First, it should be related to the curriculum. The attempt to divorce teaching and research is fatal to the life of a university department. The act of teaching makes just those demands on the understanding of a subject that are needed if a structurally sound insight is to be developed. The opportunity to expound the results of an investigation is normally essential to its healthy development and seminars play an important role at specialized research institutions where there is no regular curricular teaching. Second, fundamental research is more explicitly conscious of methodology than applied or developmental work. Little has been written in any general way on the methodology of chemical engineering. I am not here referring to particular techniques such as mathematical methods for the solution of equations of a certain sort but to the style of method in general and the peculiar character it takes on in a chemical engineering context.

BUT WHAT IS METHOD? Its etymology shows that it is concerned with a way or path

(Greek: hodos). For Descartes it was a set of "certain and simple rules, such that if a man observes them accurately, he shall never assume the false to be true nor spend his mental efforts to no purpose" [5] and he acquires this method by acquiring a sense of order. For Jeremy Bentham [6], method or, as he more frequently called it, "methodization" was primarily a matter of arrangement. It was the manner in which objects or elements of discourse are put together and so united for a particular end. This methodization by exhibition is attuned to the thinking of the Enlightenment but is far too static for a Romantic such as Coleridge [7]. For him, method arises when the mind shakes off "an habitual submission of the understanding to mere events and images" and "becomes accustomed to contemplate, not things alone, but likewise the relations of things". This generates the need "for some law of agreement or contrast between them . . . some mode of comparison". The driving force for Coleridge is the idea which provides the key-note of the harmony to follow—"an idea is an experiment proposed, an experiment is an idea realized". He sees a methodic sympathy between science and literature both of which achieve their excellence from that "just proportion, that union and interpenetration of the universal and the particular" [8]. Inspiration and methodic habit go hand in hand, confounding those who "tread the enchanted ground of poetry" without even suspecting "that

opher, Bernard Lonergan. For him the idea of method grows from a consideration of the nature of cognition. Understanding is the central act which, taken with experience and judgment, forms the basis of our knowing anything. By experience is meant the presentations of sense or the representations of imagination. Thus the understanding of the experimentalist may grow on the results of his experiments just as the theoretician's insight is grounded in his imaginative grasp of reality. Understanding grows in response to the human potentiality for wonder, which is the force behind it and provokes the question *Quid sit?* or What is it? But understanding is not an end in itself for it leads to a second question *An sit?* or Is it?—more colloquially Is that *really* so? Here a further stage of reflection is required and an element of judgment, really a judgment of existence, is called for. There is a dynamical aspect to this whole process, for judgment is called for in the decision to consider certain data of experience. Informed by the current state of his understanding the experimentalist decides what experiments he should next do. On the other hand understanding is preconceptual in the sense of being grounded in experience and finding its primary object there. It is thus to be distinguished from concept formation, where the endeavor is to find a universal notion that is not tied to the particularities immanent in experience.

Method is, in one sense, the art of understand-

It goes without saying that a close contact between industry and the university must be maintained for it is of the nature of chemical engineering to find expression in industrial processes and fundamental research must not lose sight of its final cause. It is also well to bear in mind that the cooperation of industry and university may often fruitfully follow a pattern in which the fundamental aspects are taken up by the latter but closely meshed with the questions raised by the development program.

there is such a thing as method to guide their steps." Dewey recognizes method as "intelligence in action", noting that though rules are to be followed they themselves arise from the circumstances that give them their scope for application [9]. These are but a few senses that have been brought to the notion of method, the whole concept of which has been admirably discussed by Buchler [10] and who at one point refers to a method as "a power to manipulate complexes characteristically within a perspectival order."

Let us however turn to a contemporary philos-

ing. It is, according to Lonergan, a "normative pattern of recurrent and related operations yielding cumulative and progressive results". In natural science it demands accurate observation and description, the formulation of hypotheses and their confirmation or rejection by further experience. These operations are transitive, in the sense of intending objects; they are also the conscious activity of an operator and so introspective, in the sense of elucidating the content of consciousness. Intentionality and consciousness can exist at several levels: the *empirical* level of sense

perception; the *intellectual* on which we inquire and come to understand; the *rational* on which we reflect and pass judgment; and the *responsible* level where we are concerned to evaluate and decide. Intelligence takes us beyond experience to ask what and why; reasonableness wants to know if the answers of intelligence are true; responsibility goes beyond fact and possibility to ask what is good and hence what should be put into practice. In the sense that this pattern is not tied to categories or cultural background it is transcendental and forms an objective, normative pattern of the dynamics of conscious enquiry. It must admit of further extensions and clarifications but in one sense it does not admit of revision. For a revision which destroyed the pattern would have to come from without and so be no revision but a rejection, since revision using the methods of the pattern to reject the pattern would reject itself. This transcendental method has to be worked out in a given discipline in the categories which are appropriate to that discipline. However in any context it will function in a variety of ways—normatively, critically, dialectically, systematically. It provides continuity without rigidity, guiding inquiry and laying a sound foundation.

By now the reader will be frothing at the gills "If this is what the fellow means by being more explicitly conscious of methodology, what hope is there for us? He hasn't even talked about a practical method yet." Agreed—but then Lonergan scarcely mentions God in his "Method in theology". However, just as there is a need to articulate this in detail with respect to the particular techniques of chemical engineering (as, for example, Rudd and his colleagues have done for design synthesis [13] so also is there a need to look at the foundations [14] of our style of thinking. This may lead to philosophy in the technical sense rather than in the colloquial. In the chemical engineering literature we have Rase's excellent introduction to the chemical engineering outlook [15]; in the philosophical literature there is a long tradition that has been alluded to only glancingly here—more recent modes are well described by Bochenski [16]. At all events it is not philosophy in isolation and its development and application should produce a heightened consciousness of what the chemical engineer is actually doing and help him, or her, to do it the more effectively.

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ChE book reviews

Mixing—Principles and Applications

by Shinji Nagata

Reviewed by Louis J. Jacobs, Jr., Monsanto Co., St. Louis, Missouri.

This book is a comprehensive coverage of mixing and processing of fluids in agitated vessels. A good balance between theory and practice is provided with several examples given to demonstrate use of the correlations. The late Professor Nagata of Kyoto University was one of the most active researchers in many facets of the field of mixing over the past thirty years. His qualifications to do a book of this type are without question, and we are fortunate that his manuscript was completed prior to his recent death. This book serves many purposes providing, (1) a good introduction for persons new to the mixing field, (2) a basis for people doing further research in mixing, and (3) a source of practical information for people designing mixing processes. I highly recommend this book for persons with each of these three interests.

(Continued on page 27.)

UNIVERSITY OF ILLINOIS -URBANA

Prepared by Prof. J. W. Westwater

A RECENT STUDY, "Institutional Origins of Eminent Chemical Engineers," by Siebring and Schaff of the University of Wisconsin in 1972, revealed that more eminent chemical engineers received their undergraduate degrees from the University of Illinois at Urbana-Champaign than at any other school. Of the 198 who have achieved eminence (as shown, for example, by receipt of major awards or election to national academies), 14 graduated from the University of Illinois, 13 from Massachusetts Institute of Technology, 12 from Michigan, and the rest from 76 other institutions.

In terms of the number of eminent chemical engineers who have been awarded Ph.D. degrees, Illinois ranks fifth.

Three chemical engineers who are alumni of



**J. W. Westwater,
Chairman**



the University of Illinois and are rated as eminent are now on the Urbana-Champaign campus—J. W. Westwater (B.S. 1940) and Roger A. Schmitz (B.S. 1959) of the Department of Chemical Engineering, and Thurston E. Larson (B.S. 1932; Ph.D. 1937), Assistant Chief and Head of the Chemistry Section of the Illinois State Water Survey and Professor of Sanitary Engineering in the Department of Civil Engineering.

THE BEGINNING

CHEMICAL ENGINEERING AT the University of Illinois was founded by Samuel W. Parr (1891-1927), whose portrait is on display in the first-floor lobby of the Roger Adams Laboratory. Parr developed standard methods for measuring the quality of coal. One of his inventions, the Parr calorimeter for measuring the heating value of fuels, is widely known. Illinois Industrial University (named the University of Illinois in 1886) was in existence but eighteen years when Parr was appointed an instructor in 1885. In 1891 he became Professor of Applied Chemistry and Head of Industrial Chemistry. The staff size in the entire University numbered forty-three at that time.

The University of Illinois Catalog for 1901-02 lists a curriculum entitled, "Chemical Engineering—for the Degree of Bachelor of Science in Chemical Engineering." The curriculum has continued without interruption since 1901. Clarence H. Bean was the first recipient of the degree in 1903. Two more years elapsed before the second student received the degree. The curriculum became popular in a short time. Ten degrees were awarded in 1912, twenty in 1917, and thirty in 1920.

The first book with the words chemical engineering was published in 1901, a *Handbook of Chemical Engineering* by Professor George E. Davis of the Manchester Technical School in England. The following year William H. Walker used the label on a curriculum at Massachusetts Institute of Technology. Incidentally, Walker is honored today by virtue of the William H. Walker Award for excellence in contributions to ChE literature. This award has been won by three of the present University of Illinois staff members (Drickamer, Hanratty, and Westwater), by two former staff members (Comings and Johnstone), and by three alumni (Bird, Gilliland, and Pigford).

In 1908 the American Institute of Chemical Engineers was founded, with 40 charter members. Today, there are more than 39,000 members. In 1908 there were no courses anywhere in unit operations, material and energy balances, process design, chemical thermodynamics, or applied kinetics. Thus the early curriculum operated with no textbooks in ChE. In 1922 University of Illinois course titles were Chemistry 7, Metallurgy; Chemistry 65b, Gas Analysis; Chemistry 77, Classification and Theory of Carbonization; and Chemistry 76, Tars and Oils. Of historical significance was the publication in 1923 of *Principles of Chemical Engineering*, by Walker, Lewis, and McAdams at Massachusetts Institute of Technology. This marked the emergence of ChE from chemistry.

Chemical engineering at Illinois is known for the number of publications its faculty has and the number of awards and honors it has received. Publications total about 35 per year, or an average of about four per professor.

ACCREDITATION

BY 1925 A PROCEDURE for accrediting curricula in ChE was established by the AIChE. Thirteen curricula were accredited that year and two more in 1926. The University of Illinois was not on the list, possibly because the ties with engineering were not strong enough and also because ChE was not a sufficiently independent identity.

In 1926 Roger Adams became the Head of the Department of Chemistry and D. B. Keyes (1926-45) was hired to take charge of Division of Chemical Engineering and make the changes needed for accreditation. The book by Walker, Lewis, and McAdams was adopted promptly, and the teaching of unit operations was established.

New staff members with fresh viewpoints were brought in. F. G. Straub (1924-57) had come as a Special Research Associate in 1924, and became



Fluid dynamics is investigated for a bed of regularly packed spheres.

an Assistant Professor in 1925. F. C. Howard (1926-36) and N. W. Krase (1926-36) were other additions. Sherlock Swann (1926-68) joined the research staff in 1927 and became an Assistant Professor in 1932. H. F. Johnstone (1926-62) was appointed a member of the research staff in 1928 and became an Assistant Professor in 1931. These staff members had appointments, in part at least, in the Engineering Experiment Station of the College of Engineering.

Even today there is cooperation between the College of Engineering and the College of Liberal Arts and Sciences in matters involving ChE. The present head of the Department of Chemical Engineering has a 40 percent appointment in the

College of Engineering and the rest in the College of Liberal Arts and Sciences. The other staff members are paid through their original home in L.A.S., but each has an appointment at zero pay in the College of Engineering. The ChE Department participates in important committees in the College of Engineering, including the Executive Committee and the Engineering Policy and Development Committee.

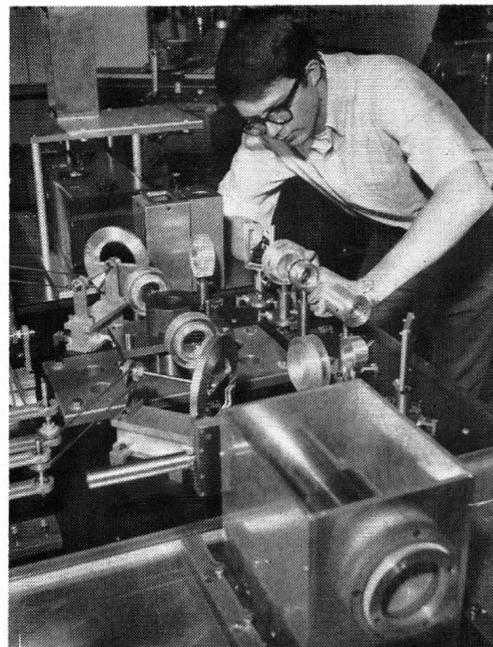
Under Keyes, the old Division of Applied Chemistry was given a new name, the Division of Chemical Engineering. The new curriculum received accreditation in 1933. The University of Illinois was the sixteenth school to be accredited. Today, the total number of accredited schools is 126.

During this period, the space occupied by the Division of ChE consisted of about one-third of the basement plus one-third of the ground floor of Noyes Laboratory. In spite of the shortage of space, the number of B.S. degrees granted per year rose to a peak of sixty in 1942. The war caused the number to decrease to eight in 1945.

GRADUATE EDUCATION GROWS

FROM 1945 TO 1955, H. F. Johnstone served as Head of the Division of Chemical Engineering. Three events of this decade merit notice. One was the planning and construction of the Roger Adams Laboratory (called the East Chemistry Building until 1972). The Division moved into the new space, with its excellent facilities, in 1950. The second event was an increase in emphasis on graduate education. The improved space made possible a significant growth in the number of graduate students in chemical engineering. Also, the goals in the recruitment of new faculty changed completely. The old emphasis on practical experience changed to an emphasis on research and graduate teaching. In the ten years preceding Johnstone's appointment as Head, the Division produced nineteen Ph.D. degrees. In the ten years which followed, the number tripled to sixty-one.

A recent study revealed that more eminent chemical engineers received their degrees from the University of Illinois at Urbana-Champaign, than at any other school.



The properties of solids are studied in the High Pressure Laboratory.

Thirdly, an option in bioengineering was introduced into the undergraduate curriculum. This was continued from 1949 to 1959 under the supervision of R. K. Finn (1949-55) and J. C. Garver (1955-57). The option was finally dropped because of disappointing job opportunities. It is possible that the department was about ten years ahead of the times. Bioengineering is being offered again at a large number of schools today in the hope that job opportunities may have improved.

In 1953 there was some administrative reorganization and the Department of Chemistry was renamed the Department of Chemistry and Chemical Engineering.

H. G. Drickamer was the head of the Division of Chemical Engineering from 1955 to 1958. He then returned to his research and teaching activities and the headship passed to M. S. Peters (1951-62). Max Peters was a gifted administrator. This fact soon became widely known, and after holding the position from 1958 to 1962, Peters went to the University of Colorado as Dean of Engineering.

Meanwhile, Drickamer achieved outstanding results with his research. This resulted in numerous honors and awards. Drickamer has the rare distinction of being honored by four different technical societies: the Allan P. Colburn Award, Alpha Chi Sigma Award, and the William H. Walker Award from the American Institute of Chemical Engineers; the Ipatieff Award and the

Langmuir Award of the American Chemical Society; the Oliver E. Buckley Prize of the American Physical Society; and the Vincent Bendix Award of the American Society of Engineering Education. Drickamer is a member of the National Academy of Sciences and a member of the Center for Advanced Studies at the University of Illinois at Urbana-Champaign. At age fifty-six he has published 260 research articles.

In 1962 J. W. Westwater was appointed Head of the Division of Chemical Engineering. From about 1955 to 1968 a national expansion in graduate education took place, encouraged by federal funds. At the University of Illinois a peak output of eighteen Ph.D. degrees in chemical engineering was reached in 1969-70. This was the second largest output in the nation (behind Massachusetts Institute of Technology). The number of faculty rose to nine, the present number. The number of M.S. degrees reached a peak of twenty-four in 1968-69, and the total number of graduate students in residence reached seventy-two at that time. This meant that the number of graduate students was nearly triple the number of seniors.

THE PRESENT

BY 1968 the decline in federal funding of graduate students and traineeships was under way. There are no more NASA Traineeships or NDEA Fellowships, and NSF Traineeships are very few. The Department of ChE has readjusted and now has approximately fifty graduate students.

In 1970 a significant administrative reorganization occurred. The former Department of Chemistry and Chemical Engineering became the School of Chemical Sciences, with H. S. Gutowsky as Director. The former six divisions became three departments: Chemical Engineering, Chemistry, and Biochemistry. Westwater was appointed head of the Department of ChE and still holds that position.

At the undergraduate level, ChE has evolved steadily. Fifty years ago the curriculum included courses in forge work, metallurgy, assaying, and fuel analysis. These had all disappeared by 1950. The last twenty years has seen the disappearance of hygiene, military, physical education, engineering drawing, ChE technology, mechanical engineering laboratory, strength of materials laboratory, and the inspection trip. The rhetoric requirement has been reduced by a third, the foreign language requirement has been eased, and the

number of credit hours required for graduation has been reduced from 136 to 129. Chemistry, physics, and mathematics have been consistently emphasized throughout the years. Course replacements have included higher mathematics; computer science; process dynamics; kinetics; prediction of physical properties; heat, mass, and momentum transfer; social studies; and humanities.

The change in graduate courses has been even faster. Of the courses offered twenty years ago, only fluid dynamics remains (but revised completely). Gone are evaporation, drying, humidification, dehumidification; absorption and extraction; filtration and separations; distillation; and advanced plant design. Course replacements have included hydrodynamic stability, properties of liquids, interfacial phenomena, ChE mathematics, reaction kinetics, advanced topics in heat and mass transfer, and a variety of research group seminars. Significant changes in the requirements

The Department concentrates on teaching ChE and leaves the service courses to the service departments. This makes possible the use of a staff of nine . . .

for the Ph.D. degree include the elimination of foreign languages. The oral preliminary examination is now concerned exclusively with the student's research.

Chemical engineering at the University of Illinois is unique in a number of respects. All of the faculty teach undergraduate courses and graduate courses and direct graduate theses. All of our seniors who wish to obtain graduate degrees are sent to other schools so as to broaden their experience; all of our graduate students are "imported" from outside schools. Our staff members are imports also; that is, their Ph.D. degrees were obtained elsewhere. The ratio of graduate students to faculty is maintained high. At present the average is 6.5 graduate students per professor—among the highest in the nation. The Department of ChE runs a tight ship. That is, it concentrates on teaching ChE and leaves the service courses to the service departments. This makes possible the use of a staff of nine, which is smaller than the staffs of other well-known ChE departments. As a rule, other ChE departments choose to teach some of their own service courses in chemistry, mathematics, mechanics, and sometimes rhetoric.

At Illinois we are fortunate in having strong service departments.

Chemical Engineering at Illinois is unique in the number of publications its faculty has and the number of awards and honors received. The publications total about thirty-five per year, or an average of about four per professor. This is near the top for chemical engineering departments.

THE FACULTY

H. G. DRICKAMER, who came in 1946, is the "old timer" of the present staff. His research on the effect of high pressure on the properties of matter is internationally famous. J. W. Westwater came in 1948. His research on heat transfer during boiling and condensation was acknowledged by the Institute Lecture and William H. Walker Award of the American Institute of Chemical Engineers, the Conference Award of the Eighth National Heat Transfer Conference, a Sigma Xi Prize, the Max Jakob Award of the AIChE and

and the kinetics of reactions in solutions won the Allan P. Colburn Award. The above listing of the full professors shows all of them have received high awards. This is rare for any department.

The future of the department depends on the abilities of the younger staff members. The two Associate Professors are R. L. Sani who investigates fluid instability and R. C. Alkire who studies electrochemical engineering. Two staff replacements at the Assistant Professor level are imminent at the time of this writing. One will replace J. L. Hudson (1963-75) who has just become Head of ChE at the University of Virginia, and the other will replace A. A. Kozinski (1971-74) who recently accepted a fine administrative position with Quaker Oats. Raids on our staff are flattering acts; they show the esteem with which outsiders view our personnel.

The present rests on the past. Former staff members not discussed above, made valuable contributions to the development of chemical engineering at Illinois. These include G. M. Smith

. . . All of the faculty teach undergraduate and graduate courses and direct graduate theses. All of our seniors who wish to obtain graduate degrees are sent to other schools so as to broaden their experience; all of our graduate students are "imported" . . . our staff members are imports also; that is, their Ph.D. degrees were obtained elsewhere.

ASME and the Vincent Bendix Award of the American Society of Engineering Education. He is a member of the National Academy of Engineering. He was general Chairman of the Third International Heat Transfer Conference, and he has served as a Director of the American Institute of Chemical Engineers. T. J. Hanratty came to Illinois in 1953. For his research in fluid mechanics he has received the Allan P. Colburn Award, William H. Walker Award, and Professional Progress Award of the American Institute of Chemical Engineers, and the Curtis W. McGraw Award of the American Society for Engineering Education. He is a member of the National Academy of Engineering. R. A. Schmitz joined our faculty in 1962. He was awarded the Allan P. Colburn Award for the excellence of his research on reactor stability. The excellence of his teaching resulted in a \$1,000 Excellence in Teaching Award from the University. C. A. Eckert came in 1965. His work on thermodynamic properties

(1905-19), D. F. McFarland (1910-20), H. J. Broderson (1913-17), T. E. Layng (1920-29), S. S. Kistler (1931-35), E. W. Comings (1936-51) recently Dean at Delaware, A. G. Deem (1938-45), Clay Lewis (1942-45) now at Georgia Tech., W. M. Langdon (1943-46) now at the Illinois Institute of Technology, Joel Hougen (1946-48) now at the University of Texas, W. M. Campbell (1947-50), L. G. Alexander (1947-50) recently at the University of Tennessee, Thomas Baron (1948-51) now president of Shell Development Company, W. E. Ranz (1951-53) now at the University of Minnesota, W. J. Scheffy (1956-59), J. A. Quinn (1958-71) now at the University of Pennsylvania, D. D. Perlmutter (1958-64) now Head at the University of Pennsylvania, and Eric Baer (1960-62) now Head of Polymer Science at Case Western Reserve. The fact that many of these men continued careers at other educational institutions demonstrates that the schools are strongly interdependent and interrelated. □

For positive results turn to McGraw-Hill texts



MASS TRANSFER

Thomas K. Sherwood, University of California, Berkeley, **Robert L. Pigford**, University of Delaware, and **Charles R. Wilke**, University of California, Berkeley. 1975, 666 pages, \$21.50

Substantially more sophisticated than the 1952 version *Absorption and Extraction*, this volume provides considerably broader coverage of mass transfer. It emphasizes the practical aspects and real problems that require an understanding of theory. Yet, the text minimizes theoretical derivations by explicitly citing over 1,100 contemporary references.

AIR POLLUTION CONTROL: Guidebook for Management

Edited by **A.T. Rossano, Jr.**, University of Washington, Seattle. 1969, 214 pages, \$19.50

Important basic principles of the chemistry and engineering of air pollution control are discussed in this comprehensive, introductory text.

SOURCE TESTING FOR AIR POLLUTION CONTROL

Hal B.H. Cooper, Jr., Texas A & M University, and **A.T. Rossano, Jr.**, University of Washington, Seattle. 1971, 278 pages, \$14.95

This informative text discusses principles and methods used for testing the gaseous and particulate materials being emitted from industrial, combustion, and other sources. The book logically explains the steps taken in source testing, and extensively examines the equipment, methodology, sampling, and analytical techniques in use for gaseous and particulate particles.

SYSTEMS ANALYSIS AND WATER QUALITY CONTROL

Robert V. Thomann, Manhattan College. 1972, 286 pages, \$19.50

Using both mathematical models of environmental responses and management and control schemes, this text 1) presents analytical tools for describing and forecasting the effects of the environment on water quality of streams and estuaries; 2) discusses water quality criteria and wastewater inputs; and 3) helps readers being evaluating the worth of water quality improvement projects. The benefits of applying cost/benefit analysis to engineering are also discussed.

ENVIRONMENTAL SYSTEMS ENGINEERING

Linvil G. Rich, Clemson University. McGraw-Hill Series in Water Resources and Environmental Engineering. 1973, 405 pages, \$18.50

Extensively using the mathematics of systems analysis and computer solutions, this text focuses on how the components of the environmental systems work as a whole rather than apart. Although considering water environment in much detail, it also discusses air pollution and its control; solid waste management, and radiological health.

AIR POLLUTION

H.C. Perkins, University of Arizona. 1974, 407 pages, \$17.50. Solutions Manual.

Written to help chemical, mechanical, and sanitary engineering students solve a variety of problems, this text includes a complete discussion of the global effects of air pollution, along with numerous applications-type problems. The material on combustion features a unique discussion of the different effects that equilibrium and reaction kinetics play in causing combustion generated pollution.

SCIENTIFIC STREAM POLLUTION ANALYSIS

Nelson Leonard Nemerow, Syracuse University. 1974, 358 pages, \$19.50

A careful balance of the hydrological, chemical, and mathematical concepts involved in the evaluation of stream quality is achieved in this comprehensive description of the analysis of water pollution. The text considers economic and management problems and presents practice problems. Other topics include chemical water qualities for different stream uses, stream management, and estuary analysis.

PROCESS MODELING, SIMULATION, AND CONTROL FOR CHEMICAL ENGINEERS

William L. Luyben, Lehigh University. McGraw-Hill Series in Chemical Engineering. 1973, 558 pages, \$19.50

Professor Luyben's book presents only useful, state-of-the-art, applications-oriented tools and techniques to help readers understand and solve practical dynamics and control problems in chemical engineering systems. Discussing actual examples and processes from his experience in chemical and petroleum industries, the author treats mathematical modeling, computer simulation, and process control in a unified, integrated way.



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1221 Avenue of the Americas
New York, N.Y. 10020

Prices subject to change without notice.

A student is only a student until you teach

ESSENTIALS OF MATERIALS SCIENCE

Albert G. Guy, University of Florida, Gainesville. Jan. 1976. 512 pages, \$17.50. Instructor's Manual.

Taking an integrated approach, the author emphasizes practical applications while covering the essential aspect of how metals, ceramics, semiconductors, and polymers behave. Using everyday examples, he shows students the connection between the behavior of familiar objects and the new concepts to be explored. Other interesting features of the book include impromptu experiments students can perform, self-evaluating questions, review questions, and problems.

HEAT TRANSFER, Fourth Edition

Jack P. Holman, Southern Methodist University. Jan. 1976. 512 pages, \$17.50. Instructor's Manual and Self-Study Cassette Tapes.

Containing both SI and English units, this introductory text includes discussions of special applications to heat pipes and environmental problems. The Fourth Edition's special features include increased emphasis on numerical methods in conduction problems, with inclusion of a generalized formulation technique; new empirical correlations for forced convection heat transfer; and an extensive rewrite of free convection correlations to reflect recent research. The **Self-Study Cassettes** for this edition comprise almost a complete course in heat transfer, are much longer than the Third Edition's, and use only the text without a separate workbook.

THERMODYNAMICS, Second Edition

Jack P. Holman, Southern Methodist University. 1974. 608 pages, \$17.50. Solutions Manual, Self-Study Cassette Tapes, & Self-Study Guide.

With this book, all standard thermodynamic topics can be covered from either the classical or statistical viewpoint, or from any desired integration of these viewpoints. The text features 60% expansion of classical thermodynamics and applications; and many new examples and problems worked in both fps and SI units. It is supplemented by **Self-Study Cassettes** of mini-lectures and discussions (approx. 9 hours running time).

PRINCIPLES OF THERMODYNAMICS

Jui Sheng Hsieh, New Jersey Institute of Technology. 1975, 512 pages, \$18.50. Solutions Manual.

A clear, unified treatment of various thermodynamic systems, this graduate level text illustrates the wide-range practicality of the basic laws of thermodynamics. Beginning with a comprehensive review of the first and second laws, it treats thermodynamic relations for single- and multi-component compressible systems; stability phase and chemical equilibrium, and other topics.

BASIC ENGINEERING THERMODYNAMICS, Second Edition

Mark W. Zemansky, Emeritus, City College of the City University of New York; **Michael M. Abbott** and **Henrick C. Van Ness**, both of Rensselaer Polytechnic Institute. 1975. 492 pages, \$16.50. Solutions Manual.

Outstanding for its broad, thorough treatment of thermodynamic fundamentals, this text makes applications to many technological processes while avoiding complex problems of a specialized nature. Important changes in the book include a consolidation and unification of material resulting in fewer chapters, the addition of many more worked examples, extensive use of SI units, and use of the same sign conventions for work and heat.

INTRODUCTION TO CHEMICAL ENGINEERING THERMODYNAMICS, Third Edition

J.M. Smith, University of California, Davis, and **H.C. Van Ness**, Rensselaer Polytechnic Institute. McGraw-Hill Series in Chemical Engineering. 1975, 632 pages, \$19.50. Solutions Manual.

Including a new chapter on solution thermodynamics, the Third Edition of this successful fundamental text is a unified treatment of thermodynamics from a chemical engineering point of view. Discussing single component systems, multicomponent systems of variable composition, partial properties, fugacity, and other topics, the book has been completely rewritten and expanded, and is enhanced by end-of-chapter problems.

AIR POLLUTION:

Physical and Chemical Fundamentals

John H. Seinfeld, California Institute of Technology. 1975, 544 pages, \$22.50. Instructor's Manual.

A quantitative, rigorous approach to the science and engineering underlying the air pollution problem, this text comprehensively treats air pollution chemistry, atmospheric transport processes, combustion sources and control methods. The author also explores the physical and chemical behavior of air pollutants in the atmosphere and methods to control them.



him or her to be a chemical engineer.

APPLIED STATISTICAL MECHANICS: Thermodynamic and Transport Properties of Fluids

Thomas M. Reed and **Keith E. Gubbins**, both of the University of Florida. McGraw-Hill Series in Chemical Engineering, 1973, 510 pages, \$21.00. Solutions Manual.

Emphasizing applications, this text introduces various ways in which statistical thermodynamics and kinetic theory can be applied to systems of chemical and engineering interests. It presents a fundamental, up-to-date treatment of statistical mechanics and focuses primarily on molecular theory as a basis for correlating and predicting physical properties of gases and liquids. Material on recent theoretical approaches i.e. perturbation theory, is also included.

CHEMICAL ENGINEERING KINETICS, Second Edition

J.M. Smith, University of California, Davis. McGraw-Hill Series in Chemical Engineering, 1970, 544 pages, \$18.50

Written to acquaint students with the tools necessary to design new chemical reactors and predict the performance of existing ones, this book develops principles of kinetics and reactor design and then applies them to actual chemical reactors. Emphasis is placed on real reactions using experimental rather than hypothetical data.

PRINCIPLES OF NON-NEWTONIAN FLUID MECHANICS

G. Astarita, University of Naples and **G. Marrucci**, University of Palermo. McGraw-Hill Series in Chemical Engineering, 1974, 304 pages, \$19.50

This advanced treatment of non-newtonian fluid mechanics includes discussions of continuum mechanics, modern dynamic theory, and rheology, which are developed to help readers solve fluid mechanics problems, particularly those associated with polymeric materials. The text takes the axiomatic approach, in which general theoretical results are obtained from as few assumptions as possible.

THE INTERPRETATION AND USE OF RATE DATA

Stuart W. Churchill, University of Pennsylvania. 1974, 510 pages, \$19.50

This book's completely new, unique treatment of rate processes is unified and generalized in terms of both procedures and processes. Greatly simplifying and reducing the number of concepts needed by the student, it provides an elementary, basic coverage of chemical reactor design, momentum transfer, heat transfer and component transfer. Concepts presented in the text are reinforced by over 300 problems based on raw experimental data from the literature.

COMPUTER-AIDED HEAT TRANSFER ANALYSIS

J. Alan Adams and **David F. Rogers**, both of the United States Naval Academy. 1973, 426 pages, \$18.50

Offering useful engineering analysis techniques, this introductory book increases students' involvement and creativity in solving heat transfer problems. It presents a balanced approach between theory and analysis/application of that theory for all three modes of heat transfer. Well-documented, interactive computer programs (BASIC) are an integral part of the text.

MASS TRANSFER OPERATIONS, Second Edition

Robert E. Treybal, University of Rhode Island. McGraw-Hill Series in Chemical Engineering, 1968, 688 pages, \$20.50

This text treats major subjects in categories of gas-liquid, liquid-liquid, and fluid-solid contact. It applies modern theories and data to the practical design of equipment and features added material on multi-component gas absorption and distillation.

UNIT OPERATIONS OF CHEMICAL ENGINEERING, Third Edition

Warren L. McCabe, Emeritus, North Carolina State University, and **Julian C. Smith** Cornell University. Jan. 1976, 1,028 pages, \$22.50. Solutions Manual.

A new revision, the Third Edition of this internationally acclaimed text now offers a thorough discussion of the three unit system: FPS, CGS, and SI units. It also introduces fugacity and activity coefficients in the study of phase equilibria, and contains a completely new chapter on multi-component distillation.

CHEMICAL AND CATALYTIC REACTION ENGINEERING

James J. Carberry, University of Notre Dame. Jul. 1976, 704 pages (tent.), \$22.50 (tent.)

Dr. Carberry's presentation embraces a diversity of heterogeneous reaction engineering phenomena. He chiefly emphasizes the heterogeneous system on both the laboratory and plant scales, in particular heterogeneous catalysis and catalytic reactors. Discussion includes chemical reaction kinetics, ideal reactor types, real reactor equations and their parameters, and other topics.

University of Florida's

John P. O'Connell

Prepared by Dick Dale, Engineering Publications, with the assistance of U. of Florida ChE Dept.

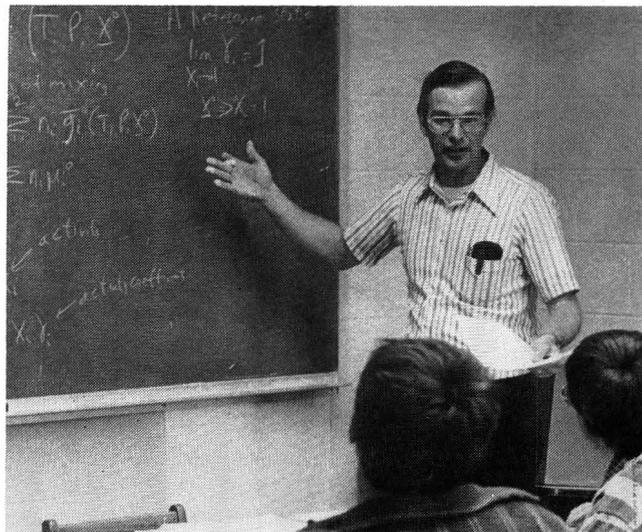
O'CONNELL ENJOYS being a teacher. He has fun at it. He has, admittedly, found his calling. "I became a teacher because of all my great teachers," he explains, "from grammar school through high school and particularly through 10 years in college and university work." (O'Connell's educational background ranges from receiving his B.A. from Pomona College, a small liberal arts college, to his S.B., S.M. from M.I.T. and his Ph.D. from the University of California at Berkeley.) "While I love all the activities of being a professor . . . teaching, research, service, most of my satisfaction comes from teaching in the broad sense. Or, better, helping *learning* in the broad sense."

"I hope to cultivate people. I want to get students to the position where they will be able to handle anything they encounter and take appropriate action, not only in work situations but in all situations."

"I like teaching engineers," he adds, with enthusiasm, "because they are the doers of modern society. Part of the leadership problems we have in all areas are people who are unwilling or unable to *do* things. I want my students to be able to act."

O'Connell says, "While there were many who influenced me, more than any other person W. K. "Doc" Lewis of M.I.T. determined my style of teaching which tries to get students to think for themselves. He recalls that, "Just talking to "Doc" was often an exhausting experience because one

**Teaching a son to play ball
applauding a musical daughter, and
taking the whole family camping are matters
of prime importance . . . to which he
devotes all of his attention and energies
with the same fervor he attacks
teaching, research or academic affairs.**



. . . a love affair with the classroom

had to be constantly alert. But you could learn much because "Doc" was so intuitive about how nature behaves. He always knew the physics of the situation."

As a result of this experience, O'Connell is a man who prowls his classroom hurling questions in response to questions, and to student's answers often gives the frustrating challenge of, "Do you *really* believe that?" But, though the vital young educator admits to a love affair with the classroom, his real love is informal interactions with one student, head to head, or with several in a close contest. Such occasions, be they "bull sessions or counselling sessions, allow me to deal with the students as individuals and give them what I've learned and valued." Unfortunately, this is not 'efficient' in the bugetary sense. Because we are developing people, education is not a matter of production. If we must, a better way to cut costs is to reduce that proportion of students that are not eager to get all they can out of their educational opportunities. We in public institutions

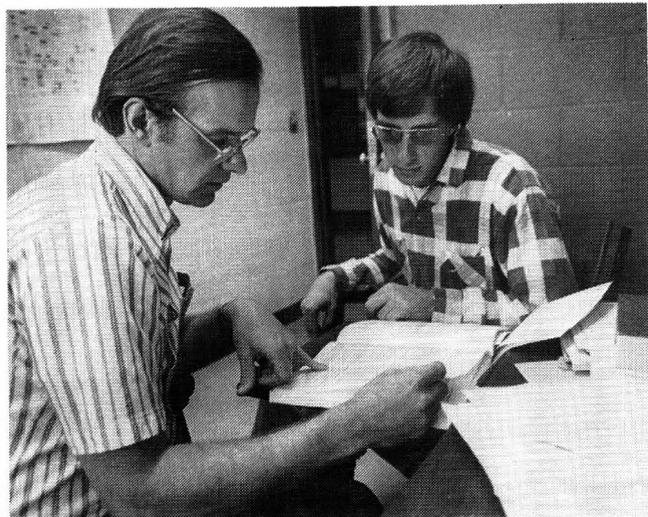
should try to establish an atmosphere of intellectual pursuit and tradition found usually at private schools where students are carefully selected.

REACHING BACK

RECENTLY, THROUGH the latter half of his nine years of teaching, he has noted in his students two trends, one is a move of sorts toward tradition, a return to the ceremonial, a reaching back. And this meets with his approval. "We have such a rich variety of things that we can get into and enjoy. We have the opportunity to go back and rediscover and reappraise so very much."

The second is that even though modern chemical engineering students are more concerned about reaching successful employment and a career than a few years ago, "They are not as selfishly motivated as this usually implies and as students may be in other fields of study," he continues. "They help each other and are more sensitive to each other. This is great, because I feel many of the problems of the world exist because people are insensitive to one another."

How does O'Connell come across? Well, Professor Robert Bennett, an associate and an admirer comments, "The impression we get from John's students is that he is extremely interested in their welfare, growth, learning and understanding. He will spend hours with a student trying to



His real love is informal interactions with one student . . .

help him understand some point. He will use every possible method to keep his students alert, make them think for themselves, including sarcasm, kidding and prodding them to take logical subsequent steps until they answer their own question.

O'Connell recalls, "More than any other person 'Doc' Lewis influenced my style of teaching . . . adopting the Socratic method to make students think. Just sitting talking to 'Doc' was an exhausting experience."

They see him as having unbounded physical, emotional and mental energy that sometimes leaves his listener gasping for his breath."

John M. Prausnitz writes from Berkeley about O'Connell's influence there: "As elsewhere, new graduate students at Berkeley are assigned a desk and chair soon after arrival. All too often these desks and chairs are worn, routine pieces of furniture devoid of any charm or personality.

"Soon after John's arrival at Berkeley he too was given a hum-drum old chair and desk. Not very pleased, John scouted around the various storerooms of the College of Chemistry and somewhere he found an antique, upholstered swivel chair—not luxurious—but much more comfortable than the assigned one and definitely interesting, colorful and unique. John O'Connell claims an aged janitor told him he had cleaned that chair for over 40 years and that it originally belonged to the late Professor Latimer, discoverer of the hydrogen bomb when he was dean of the college.

"The chair is now the prize possession in the molecular-thermodynamics research laboratory. By tradition it is used by the senior graduate student, sometimes with a little ceremony. Although it lacks an endowment, the O'Connell Chair is high in prestige."

IN A PICKLE

ONE CLASS OF JUNIORS at Stanford was so enthusiastic, but overwhelmed by the learning experience with O'Connell's thermodynamics course that they established the first annual Chemical Engineering "Pickle Award" in honor of "what they were in all term long." The award was a large Kosher Dill Pickle. Returning to give a Seminar at Stanford one year later, he also received the second Pickle award since no suitable successor could be found among the Stanford faculty. John says "That class was one of my great teaching experiences because I had the time to devote to the students and they not only had great ability, they all really wanted to learn. Apparently I was one of the few teachers they had that they felt really cared."

O'Connell's more recent academic activities include belonging to such professional societies as ASEE-CED, AIChE, the American Chemical Society, the American Association of University Professors, the American Association for Advancement of Science. People who have shared committee service with O'Connell note that he has sensitivity, understanding, wide knowledge of the university, good rapport with campus people and is willing to take suggestions. They also say that as a committee member he is a "mover" and a "shaker". For example, he was the principal developer of the University of Florida Teaching Evaluation system which allows individual colleges to choose their own instrument. "While any system can be abused, I think the value of the information which should help improve teaching and of forcing many students to think about the quality of their education outweighs possible 'popularization' of courses and manipulation for wrong ends."

He is also a Danforth Associate, a program for selected faculty established by the Danforth Foundation to "promote the personal dimension of education".

O'Connell's professional fields of interest include applied statistical mechanics and molecular studies, solution thermodynamics (including electrolytes), transport properties of gases, adsorption and surface diffusion, materials and computer calculations. In addition to the usual graduate research direction, he has had a number of undergraduates work directly with him in these areas.

In his private life he concentrates his interest on his family. Their favorite activity "Which happens too infrequently", is travel and camping in their pick-up camper. He particularly enjoys watching the growth of his two sons and one daughter with their diverse talents and personalities. While John devotes the same energy and enthusiasm to their development, he does find limits to their patience with his teaching style. He also "too infrequently" enjoys the products of his wife's culinary expertise, renowned not only among faculty and students in Gainesville, but also among professional visitors fortunate enough to have a dinner or party given in their honor at the O'Connell home.

If all the foregoing paints an unusual picture of John P. O'Connell, it must certainly be founded in fact. In his own words O'Connell says:

"Any one who professes to be a thermodynamicist has got to be a peculiar person!" □

Emphasis on Quality

Sir.

Our ad on page 252 of CHEMICAL ENGINEERING EDUCATION, Volume IX, No. 4, Fall 1975, contains a more-or-less egregious error: the substitution of the word "equality" for the word "quality".

We recognize the importance of CHEMICAL ENGINEERING EDUCATION and appreciate the amount of work that goes into preparing such a publications. Thank you for your efforts.

Noel de Nevers
University of Utah

Editor's Note: *CEE* regrets this typographical error. The corrected ad appears below.

Fall Issue Feedback

Sir:

In the Fall 1975 issue of your Journal, an article by Donaghey discusses "Critical Path Planning of Graduate Research." This paper is somewhat misleading, because it indicates that the process is performed just once per project.

The sequence that Donaghey describes in his Table II does not stop with Tasks 8 and 9, because the Task 8

CONSIDER UTAH

This is a small ad for people who recognize that bigger isn't necessarily better. The University of Utah has a small chemical engineering department (8 faculty) where the emphasis is not on size but on quality. If you are interested in a small, high-quality chemical engineering department having a variety of important research activities and located in one of the world's most pleasant cities in a unique geographical setting,

write for more information to:

Professor Noel deNevers
Director of Graduate Studies
Department of Chemical Engineering
University of Utah
Salt Lake City, Utah 84112

(Compare Theo and Expt) almost always reveals an unsatisfactory level of agreement. So it is necessary to go through the cycle again, perhaps with a better definition of the problem, and a different choice of material (e.g. higher purity) etc. The cycle is repeated, over and over; and improvement of agreement (Task 8) in successive cycles is what tells the research worker that he is changing his parameters—and his concepts—in the right direction. This is a feedback process, of course.

At the start of *each* cycle, the worker should carry out a critical path analysis, in order to optimize his project plan.

Donaghey's contribution is an important one; but it needs amplification in regard to the cyclic, feedback process, and to epicycles on the main process and to the criteria which are used to terminate the research.

Robert J. Good
State University of New York—Buffalo

The Chemi Project

ORIGINALLY FORMED in 1971 to meet the need for introducing computer usage into the curriculum, The CACHE Corporation, successor to The CACHE (Computer Aids for Chemical Engineering Education) Committee, is now addressing itself to the even greater challenge of producing educational material geared to the more rapid infusion of new subject matter into the curriculum, more cost-effective training methods, increasing student problem-solving competency, and the generation of non-traditional texts and expository training material.

In an effort to achieve these goals, CACHE formed several task forces, one of which was on modularized instruction. Aware of the interest in self-paced instruction and the improved student learning from such instruction, (as evidenced by growing attendance at teaching institutes and numerous articles [1, 2, 3, 4]), the task force prepared a proposal for the NSF to produce self-study modules for use by undergraduate ChE students and also for continuing education. In July of 1975 a \$150,000 NSF Grant, over a three year period, was awarded to CACHE, for The CHEMI (Chemical Engineering Modular Instruction) Project. The grant is specifically for producing and distributing self-study, single concept, text (print) modules in ChE. These modules will cover the entire ChE undergraduate curriculum. From 40 to 70 modules are planned in each of seven curriculum areas: control, transport, stagewise processes, design, material and energy balances, kinetics, and thermodynamics. They are intended as lecture and textbook supplements for students self study, student evaluation, and concept demonstrations in the case of those modules which embody simulation type of computer programs. Also, once the modules are written, path finding algorithms will be used to trace prerequisite skills and develop curriculum guides which may be useful for ordering the modules and helping curriculum planners.

What is a module? The word "module" has several meanings in different contexts. Tosti [5] and Koen [6] have defined an educational module as follows: "A module is a self-contained section of learning material that covers one or more topic areas. It should be sufficiently detailed that an outside evaluator could identify its educational objectives and evaluate."
(Continued on page 52.)

ACKNOWLEDGMENTS

The following companies donated funds for the support of

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We also thank the 133 Chemical Engineering Departments who contributed to the support of CEE in 1975!

ALKALINE FADING OF ORGANIC DYES: AN IDEAL REACTION FOR HOMOGENEOUS REACTOR EXPERIMENTS

RONALD P. ANDRES

Princeton University

Princeton, New Jersey 08540

and LLOYD R. HILE

California State University

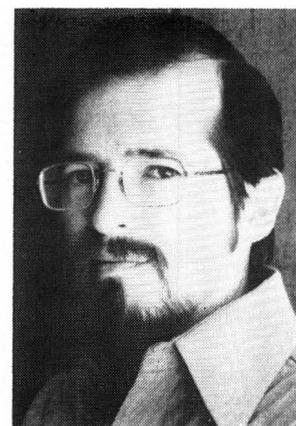
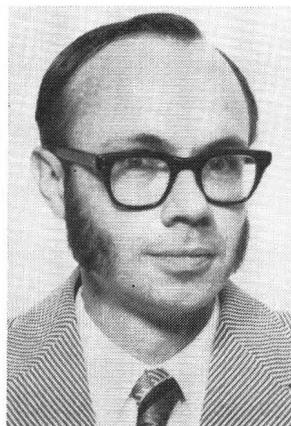
Long Beach, California 90840

THIS ARTICLE SUMMARIZES our experience using the alkaline fading reaction of certain organic dyes as a means of introducing students to the behavior of homogeneous reactors.

Since the fall of 1960, the Department of Chemical Engineering at Princeton has had a Chemical Reactor Laboratory as an integral part of its undergraduate curriculum. Initially offered as an elective for seniors in the spring term following a fall lecture course in kinetics of chemical processes, it is now combined with the lecture course and is taken by all departmental seniors. The Chemical Reactor Laboratory owes its existence to the late Richard H. Wilhelm who conceived the idea and provided the inspiration and guidance for its successful implementation. It has been described in some detail by J. B. Anderson [2], who was instrumental in the laboratory's development. The experiences described here were gained not only in the laboratory at Princeton, but also in similar laboratories at the University of Arizona and California State University, Long Beach.

An important component of the laboratory is the study of a single homogeneous reaction in batch, CSTR, and tubular flow reactors as a unified base for comparison and understanding of reactor systems. This concept forms an integral part of many similar reactor labs throughout the country. The reactions most commonly used for this purpose are the hydrolysis of acetic anhydride or

the saponification of ethyl acetate. Data is typically collected by direct sampling and titration. Our experience with this procedure is that about one-third of the groups fail to get acceptable results because of poor planning and poor experimental techniques, and all of the groups become frustrated by the tedium of many titrations. In an attempt to provide a better environment for experimental success and to increase the possibilities for examining various pertinent supplementary effects within the time constraints of the laboratory, we have recently replaced this classic re-



Ronald P. Andres received his B.S. degree from Northwestern University and his PhD degree from Princeton (1963). He is presently an associate professor of chemical engineering at Princeton University. His research interests are in rarefied gas dynamics, kinetics of nucleation, interfacial phenomena, aerosol physics, intermolecular forces, and the application of interactive computers to process control and design.

Lloyd R. Hile received B.S. degrees in chemistry and chemical engineering at the University of California, Berkeley and M.A. and Ph.D. degrees from Princeton University. He has pursued interests in undergraduate education since serving as coordinator of a newly formed ChE. program at California State University, Long Beach and recently shared experiences in laboratory development during a sabbatical at Princeton University and the University of Arizona. His teaching and research interests include kinetics, separation operations and process dynamics. (right)

*Chemical Engineering Department, California State University, Long Beach, California 90840.

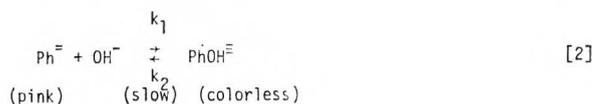
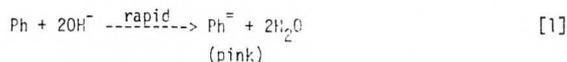
action with the alkaline fading of an organic dye. Use of such a reaction has the following advantages:

- Extent of reaction easily monitored continuously.
- Wide range of rate constants possible.
- Understanding of phenomena reinforced by visualization.
- Minimal safety hazards, waste processing problems, and chemical costs.

While our selection of an "ideal" reaction system for homogeneous reactor experiments is not unique, we feel that it offers considerable advantages that may not be widely recognized.

ALKALINE FADING OF DYES

BROMOPHENOL BLUE, crystal violet, malachite green, and phenolphthalein all undergo a slow decolorization upon combining with hydroxide ion. For example, when phenolphthalein (Ph) is added to an alkaline solution it first undergoes a rapid irreversible conversion to the quinoid form (Ph⁻) which has a pink color (absorbance peak of 550μ). The quinoid form then slowly and reversibly reacts with hydroxide ion to form the nonresonant (hence colorless) carbinol form (PhOH⁻). Presumably the reactions are:



The kinetics of reaction (2) are conveniently studied by following the decolorization of the reacting mixture using a colorimeter or spectrophotometer. We chose the phenolphthalein reaction because it illustrates a number of important concepts:

1. Coupling of Kinetics and Thermodynamics

Since the reaction is reversible, the coupling of kinetics and thermodynamics is demonstrated. The heat of reaction (from equilibrium studies at various temperatures) can be related to activation energies (from kinetic studies at various temperatures). Also, this reversible behavior adds an interesting additional complexity to the kinetic analysis. Note the other dyes mentioned above fade irreversibly.

2. Rate Determining Step

Since step (1) is essentially instantaneous, the reaction rate is determined solely by step (2).

3. Pseudo-Rate Constant

In practice $[\text{OH}^-] \gg [\text{Ph}]$ (typically 10^{-1}M vs 10^{-5}M) so the concentration of base remains effectively constant over the course of the reaction and a pseudo-rate constant can be defined. This also has the practical advantage of allowing the experimenter to select the time scale of his kinetic runs by suitable choice of hydroxide concentration. A 0.1 N hydroxide concentration provides a "half-life" of about 7 minutes at room temperature while doubling the concentration to 0.2 N shortens the half-life to about 2 minutes.

4. Salt Effect

In reactions between ions the rate "constants" are concentration dependent. The effect of positive ions in the solution is to shield the negative

**The reaction most commonly used
... is the hydrolysis of acetic anhydride.
Our experience with this procedure is
that about 1/3 of the groups fail to get
acceptable results because of poor
planning and poor experimental techniques,
and all of the groups become frustrated
by the tedium of many titrations.**

charges of Ph⁻ from OH⁻, decreasing the coulombic repulsion of these species and thus increasing the frequency with which they collide. Thus the ionic strength of the reaction mixture has an important effect on the kinetics. The Bronsted-Debye limiting law is helpful for quantifying this effect (ref. (3)).

The use of this reaction in a batch reactor and in a CSTR sequence will be briefly discussed.

ISOTHERMAL BATCH REACTOR

THE EXPERIMENT IS performed in conventional glassware with thermostatic temperature control. The reaction is initiated by rapidly mixing a few drops of phenolphthalein solution (ethyl alcohol solvent) into a dilute aqueous NaOH solution of known concentration and is followed by continuously monitoring on a spectrophotometer the absorbance of the reacting mixture with time. To avoid removing discrete samples for analysis the reaction mixture is recycled through a flow-through cell in the spectrophotometer as shown in Fig. 1. An easily constructed

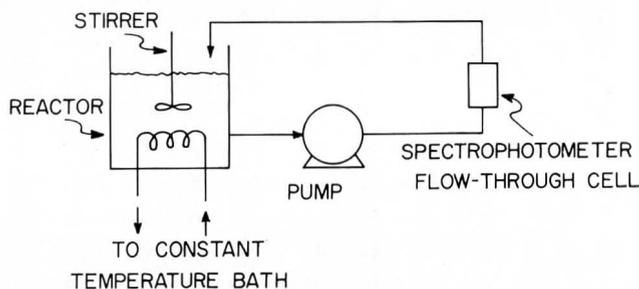


FIGURE 1.

flow-through cell is shown in Fig. 5 (cf. reference (5)). The volume of reacting fluid in the reactor can be quite small; the reactor vessel is really only needed to insure good mixing and temperature control. Care must be taken to avoid forming air bubbles in the recirculating system as this will affect the absorbance of the solution.

Postulating the rate law for reaction [2] to be

$$-r_{\text{Ph}^-} = k_1[\text{Ph}^-][\text{OH}^-] - k_2[\text{PhOH}^-] \quad [3]$$

and noting at equilibrium ($t \rightarrow \infty$) that

$$K = \frac{k_1}{k_2} = \frac{[\text{Ph}^-]_0 - [\text{Ph}^-]_\infty}{[\text{Ph}^-]_\infty [\text{OH}^-]_\infty} \quad [4]$$

it follows for the batch reactor, since $r_{\text{Ph}^-} = d[\text{Ph}^-]/dt$

$$\frac{[\text{Ph}^-] - [\text{Ph}^-]_\infty}{[\text{Ph}^-]_0 - [\text{Ph}^-]_\infty} = \exp[-(k_1' + k_2)t] \quad [5]$$

where

$k_1' = k_1[\text{OH}^-]$, pseudo first order rate constant
 $[\text{Ph}^-]_0$ = concentration of colored species at instant of initiation

Note the reaction is within 5% of equilibrium when $t = 3/(k_1' + k_2)$. If the Beer-Lambert law is followed*, concentration is directly proportional to absorbance A and

$$\ln \frac{A(t) - A(\infty)}{A(0) - A(\infty)} = -(k_1' + k_2)t \quad [6]$$

Plotting $A(t) - A(\infty)$ ** vs. t on semilog paper should yield a straight line of negative slope

* This can be tested by finding $A(0)$ (by the extrapolation procedure described) for several levels of $[\text{Ph}]$ (total phenolphthalein concentration in both forms: Ph^- and PhOH^-). A plot of $A(0)$ vs. $[\text{Ph}]$ should be linear.

** Alternately $A(t) - A(t + \Delta t)$ can be plotted where Δt is a constant time interval. The intercept is then $[A(0) - A(\infty)](1 - \exp[k_1' + k_2]\Delta t)$.

($k_1' + k_2$). Figure 2 shows such a plot of student data. Note that $A(0)$ need not be directly measured, it can be found from the intercept of the above plot. The separate rate constants are then extracted by noting from Eq. [4]

$$k_2 = \frac{k_1' + k_2}{K[\text{OH}^-] + 1} \quad [7a]$$

$$k_1 = Kk_2 \quad [7b]$$

where

$$K = \frac{A(0) - A(\infty)}{A(\infty)[\text{OH}^-]} \quad [7c]$$

The heat of reaction may be easily determined by changing the temperature at the end of a run, waiting for a new equilibrium to be established, and measuring the new absorbance $A(\infty)$ (note that $A(0)$ is not affected). A van't Hoff plot of $\ln K$ vs $1/T$ should yield a straight line of slope $-\Delta H_r/R$.

By carrying out kinetic runs at several temperature levels the activation energies and pre-exponential factors can be determined from an Arrhenius plot ($\ln k$ vs. $1/T$). The ionic strength

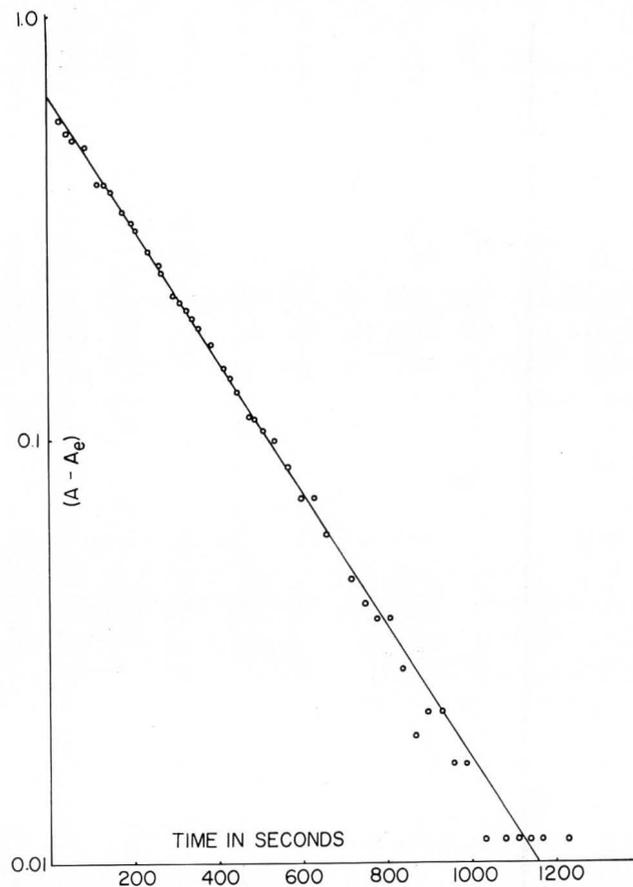


FIGURE 2.

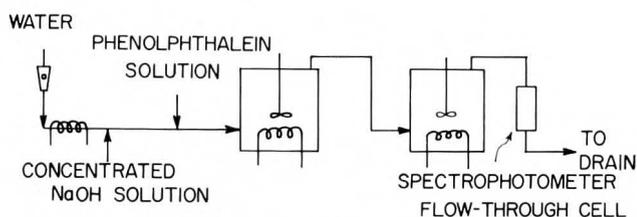


FIGURE 3.

must be the same at all temperatures used in constructing this plot.

The effect of ionic strength can be examined by studying the kinetics using several hydroxide ion concentration levels at a fixed temperature. Alternately an inert salt can be added to raise the ionic strength. An instructive question to ask the students is how they could test the presumed first-order dependence with respect to $[\text{OH}^-]$. Repeating the experimental procedure using several $[\text{OH}^-]$ levels will *not* be sufficient since k_1 is dependent on the ionic strength. A possible way out of this dilemma is to add an inert salt to maintain the ionic strength at the same level in all runs. More detailed information on these reactions is available in references [3] and [4].

CONTINUOUS STIRRED TANK REACTORS

A SERIES OF TWO isothermal stirred tank reactors are used as shown in Fig. 3. Dilution water is fed from a constant-head tank through a rotameter and through a heat exchange coil in a constant temperature bath before entering the first reactor. The NaOH solution is fed by a variable speed metering pump and the phenolphthalein solution by a variable speed syringe pump directly to the first reactor. "Start-up" is studied, in which a step input of phenolphthalein is introduced at $t = 0$. Prior to this the tanks are emptied and the water-NaOH mixture is fed into them at the chosen flow rates so the concentration of NaOH throughout the system is constant during the run. Flow rates, concentrations, and temperatures are selected which will give comparable effects of convection and reaction, i.e., a mean residence time comparable to the "half-life" for reaction. The transient response of the system to the step input of Ph is continuously followed by monitoring the absorbance of the effluent from the second tank. Due to the very low flow rate of Ph solution required, the total flow to the system is not significantly affected by the start up.

Once steady state has been achieved, the effluent from the first tank is diverted through the

flow-through cell using a line which bypasses the second tank. The feed stream absorbance could be similarly measured. Finally a sample of one of the steady-state effluents is allowed to reach equilibrium at the operating temperature and its absorbance is measured. A convenient way to accomplish this is to allow the bypassed second tank to operate as a batch reactor and sample by recycling as described in the previous section. While waiting for equilibrium in the second tank, if the feed of Ph to the first tank is stopped then the transient response to a "shut down" can be continuously monitored.

The unsteady-state material balance assuming ideal CSTR's yields the sequence of coupled linear differential equations:

$$\frac{d}{dt} \begin{bmatrix} x_1(j) \\ x_2(j) \end{bmatrix} = - \begin{bmatrix} (k_1'\theta + 1) & -k_2\theta \\ -k_1'\theta & (k_2\theta + 1) \end{bmatrix} \begin{bmatrix} x_1(j) \\ x_2(j) \end{bmatrix} + \begin{bmatrix} x_1(j-1) \\ x_2(j-1) \end{bmatrix} \quad [8]$$

θ = mean residence time in each tank
(equal volumes assumed); $t' = t/\theta$

$$x_1(j) = [\text{Ph}^-]_j / [\text{Ph}^-]_0$$

$$x_2(j) = [\text{PhOH}^-]_j / [\text{Ph}^-]_0$$

(j denotes tank number; 0 refers to feed stream). For a step input of Ph^- to tank 1 the solution to Eq. [8] can be found by standard methods (cf. ref. (1)) to be

$$x_1(j) = \frac{1}{K'+1} \left[\alpha^j K' (1 - e^{-t'/\alpha}) \sum_{n=0}^{j-1} \frac{(t'/\alpha)^n}{n!} + 1 - e^{-t'} \sum_{n=0}^{j-1} \frac{(t')^n}{n!} \right] \quad [9]$$

where $1/\alpha = (k_1' + k_2)\theta + 1$ and $K' = k_1'/k_2$. The above presumes that initially there is no phenolphthalein in any tank and that negligible conversion to PhOH^- occurs in the feed stream. Since Eq. [9] is somewhat cumbersome students may prefer to solve Eq. [8] numerically on a digital computer. Eq. [9] suggests a convenient form for displaying experimental data: a semi-log plot of $1 - A(j)/A^{ss}(j)$ vs. t/θ where $A(j)$ is the absorbance of effluent from tank j and $A^{ss}(j)$ is its steady-state value (Beer's law assumed). The shutdown case is modeled in an analogous manner.

The rate constants k_1' and k_2 may be obtained from the batch studies described previously if the same conditions of base concentration and temperature are used in this CSTR study. Alternatively there is enough information to obtain them

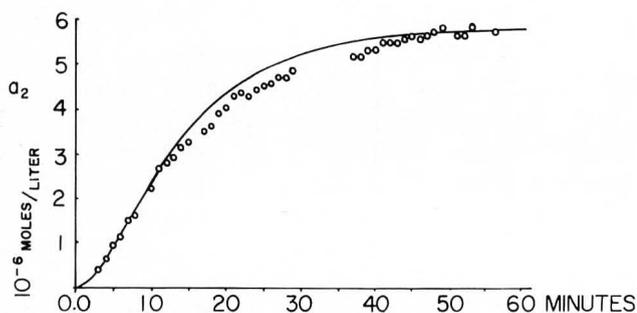


FIGURE 4.

from the steady-state measurements described above since from Eq. [9]

$$x_1^{SS}(j) = \frac{\alpha^j K' + 1}{K' + 1} \quad [10]$$

or rearranging

$$\alpha K' = A^{SS}(1)/A(\infty) - 1 \quad [11]$$

$$\alpha = [A^{SS}(2) - A(\infty)] / [A^{SS}(1) - A(\infty)]$$

where $A(\infty)$ is the absorbance of an equilibrium sample.

Note that three measurements (e.g. $A^{SS}(1)$, $A^{SS}(2)$ and $A(\infty)$) are needed to extract the rate constants k_1' and k_2 .

Comparison of the predicted and measured transient responses is shown in Fig. 4 for typical student data.

CONCLUSIONS

THE ATTITUDE OF the students to the sequence of reactor experiments was substantially improved through use of the alkaline fading reaction. Some of the poorer students had conceptual difficulty with the reversible nature of the phenolphthalein reaction, and care had to be taken that they not only made all necessary measurements but also were on the right track in developing a kinetic model to represent the experiment. Even some better students made the common error of assuming ($[\text{Ph}^-] + [\text{PhOH}^-]$) constant in the transient CSTR experiment, i.e. confusing batch and flow behavior.

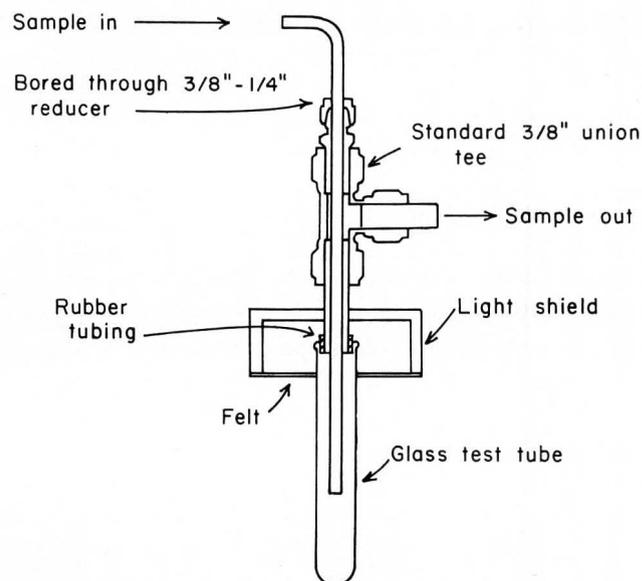
The visual nature of this reaction as carried out in clear glass reactors added considerably to the interest and gave tangible reinforcement of concepts that raw data often lacks. This allows misconceptions or blunders to be more easily uncovered. Some examples: the reversible nature of the reaction is obvious since the color never fades

completely; it is evident that the final color darkens with increasing temperature so the reaction must be exothermic; in the CSTR experiment the steady-state concentrations are noticeably different in the tanks and the distinction between equilibrium and steady state is seen; the moment of initiation can be established visually; and accidental contamination due to careless cleaning is immediately evident.

As the major objective of these experiments is to emphasize reactor properties rather than reaction properties, perhaps one of the simpler irreversible reactions should be used. On the whole, however, we feel that the new insights brought about through use of the more complex kinetics outweigh the drawbacks of a more involved experiment and analysis.

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Schematic of flow cell.

FIGURE 5.

DIGITAL SIMULATION

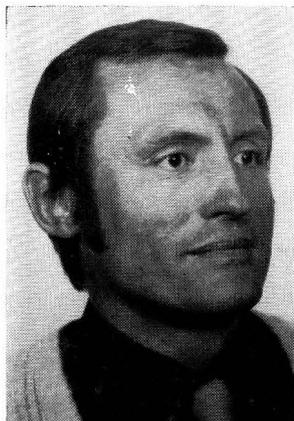
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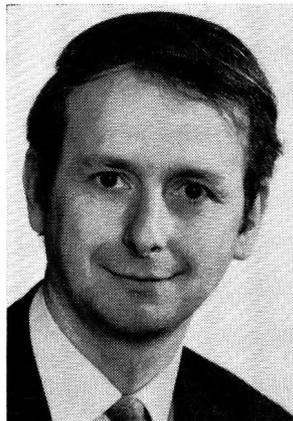
CONVENTIONAL CHEMICAL engineering laboratory courses are often found to be unsatisfactory owing to their routine, predictable nature and lack of challenge. The normal steady state approach can cause difficulties when one is confronted with real-life variable operating conditions. At present, there is a growing realization of the importance of process dynamics, even at the preliminary design stage, in order to optimize design and to implement optimal control strategies. This interest is reflected by the rapidly increasing number of new texts dealing with the

mathematical modelling, simulation and control of chemical plants [1-5]. This growing interest in the dynamic state should, we consider, be reflected by a changed emphasis in the method of teaching chemical engineering. Today at least one recent text is available in which unsteady state formulations are used at the onset to introduce students to chemical engineering analysis [6]. Based on the concept that "simulation makes you think" the present course has been developed to bring process dynamics (via the use of mathematical modelling and digital simulation programming) into the chemical engineering laboratory.

In developing the laboratory course, we were motivated by the conviction that the best way to understand the physical processes is through the use of dynamic modelling techniques. Often transient processes are more easily visualized than the steady state. Perhaps it is a matter of daily ex-



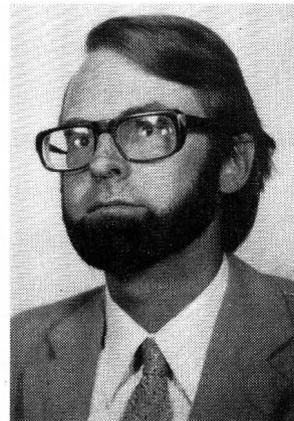
Jiri E. Prenosil was educated at the Prague Institute of Chemical Technology and received his Ph.D. degree in Chemical Engineering from the Czechoslovak Academy of Science. He has four years teaching experience at the University of Baghdad and since 1971 he has been at the Chemical Engineering Department of the Federal Institute of Technology, Zurich. His teaching and research interests are in the fundamentals of mixing and diffusion. (left)



simulation. This paper was prepared during a one year leave of absence from Bradford spent at the ETH Zurich (1971-72). (center)

Irving J. Dunn studied chemical engineering at the University of Washington in Seattle (B.S. degree, 1960) and at Princeton University (Ph.D., 1963). After periods spent at the Physical Chemistry Institute in Munich, the University of Idaho, and Robert College (now Bosphorus University), Istanbul, Turkey. Dr. Dunn is now at the ETH, Zurich. Present interests lie within the development of research programs in biochemical engineering. Current research includes oxygen transfer in fermenters, tubular loop fermenter design, on-line computer use and the control of biological sewage treatment systems. (right)

John Ingham was educated at the University of Leeds (B.Sc. 1957) and received his Ph.D. degree at the University of Bradford (1970). After several years spent in industry he is presently lecturer in chemical engineering at Bradford where his present research interests lie in the hydrodynamics of solvent extraction columns and computer



perience which allows the student to understand the physical meaning of the rates of accumulation of mass and energy within a system rather easily. Steady state conditions can then be presented as a special case in which input rates exactly balance output rates.

Probably the main reason for avoiding the study of dynamics in the past has been the difficulty in solving the mathematics. Students are easily discouraged and distracted from basic modelling processes when confronted by apparently complicated sets of simultaneous differential equations. The use of a digital simulation programming language can be employed to great advantage in these cases, even when an analytical solution is available. Writing the governing differential equations requires a detailed mathematical description for such component in the process. A clear understanding is necessary and the physical interrelationship and simultaneous nature of the equations must be fully realized. The mathematical model and its derived information flow diagram both contribute to a clearer qualitative picture of the process, as well as providing a means to eventual solution. Our experience has shown that students rapidly obtain a confidence in their mathematical ability and an enjoyment in the description of complex systems, with an increased understanding of the processes actually involved. The lack of formalism in the simulation programming, as compared to conventional computer programming, brings the students into an easy and confident relationship with the computer at a very early stage of development, since the programming is greatly simplified. Thus the student can concentrate on understanding the problem and translating his knowledge into appropriate mathematical terms.

DYNAMIC SIMULATION

THE CHEMICAL ENGINEERING program at the Swiss Federal Institute of Technology (ETH) has undergone considerable development within the last five years [7]. Students receive instruction in unit processes together with chemical reaction engineering, fluid mechanics, process control and process design and planning. A variety of laboratory courses, totalling approximately ten hours per week during one and a half years introduce the students to practical work in the fields of separation techniques, fluid flow, heterogeneous catalysis, heat transfer, measurement methods, chemical reaction engineering and process

dynamics. The final eighth half year is devoted to a full-time independent three-month research or design project.

The laboratory course, of which the simulation experiments make up a part, is taken during the first half of the fourth and final year. The students have previously been exposed to the general concepts of transient heat and mass balancing problems, but may have difficulties when confronted by real physical situations, requiring a mathematical description in dynamic terms, although about one quarter of the students take a previous elective course dealing with modelling and simulation. The total time allocated, ten hours

Based on the concept that "simulation makes you think", the present course has been developed to bring process dynamics (via the use of mathematical modelling and digital simulation programming) into the ChE lab.

per week for a period of four weeks for each experiment includes all aspects of the work: preparation, experiment, computation, interpretation and report writing.

The students receive a written outline of the experiment, together with references to the underlying theory which is discussed with an instructor. The work is then carried out more or less independently, with only occasional consultation required.

Although few aspects of the experimental equipment as described in the next section and the methods of process analysis are really new, the construction of appropriate mathematical models for real processes and the manipulation of the models on large scale computers represent a new phase in the development of chemical engineering laboratory courses.

The increased educational value is apparent when compared with the conventional steady state approach, as shown in Figure 1. The tasks involved tend to be very routine and with little active thought on the part of the student. On the other hand, the simulation of the dynamic experiments forces a positive interaction between the development of the mathematical model and the experiment. Moreover, the experimental results have their theoretical counterpart which can be used for the instantaneous control of both experi-

ment and model. This is illustrated in Figure 2.

The task of obtaining a solution is very significant in the learning process. All parameters must be defined and any forgotten parameter will be clearly indicated by the computer. The need to define initial conditions forces the student to consider the nature of the physical situation. Any error in any of the parameters will usually lead to results which are physically unreasonable; again forcing the student to analyse the problem with care. Thus, the success of the computer simulation provides a check on the mathematical model. Agreement between experiment and theory greatly improves the students' confidence and ability.

Discussion often arises regarding the correct choice of the factors to be included in the model. These questions often lead to further experiments in order to confirm the assumptions concerning the actual physical situation. Simplifying assumptions in the model may also be suggested.

Although the students have only moderate prior computer experience, they generally have little difficulty in using the MIMIC digital simulation programming language. Thus the step from mathematical model to the numerical solution proceeds with little effort, leaving the students free to concentrate on understanding the nature of the physical system, formulating this into mathematical terms, and determining appropriate numerical parameters. We have found the use of the simulation language to be a significant teaching

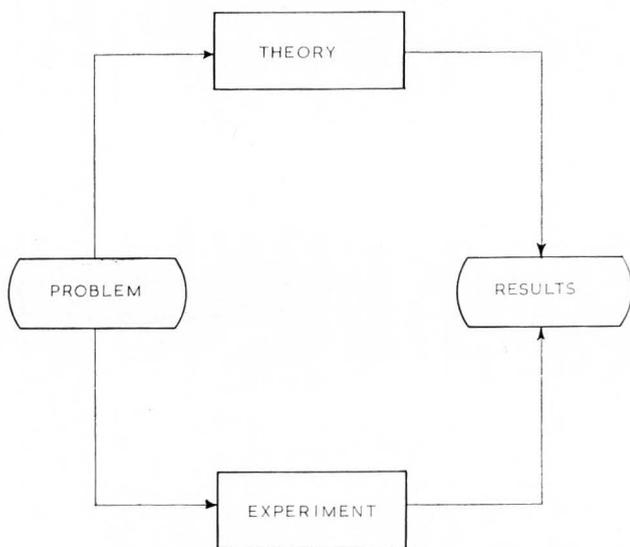


FIG. 1 CONVENTIONAL LABORATORY COURSE

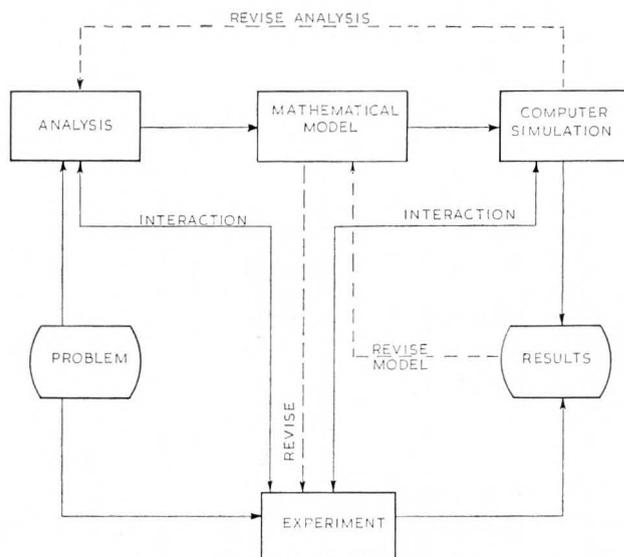


FIG. 2. SIMULATION LABORATORY COURSE

aid, contributing greatly to student motivation and interest.

THE EXPERIMENTS

A SERIES OF SIX experiments are presently employed. These involve the study of the dynamic response characteristics of:—

- a cascade of stirred tank reactors,
- a tubular chemical reactor,
- a liquid level control system,
- a batch distillation,
- the transient heating and cooling of a batch reactor vessel and contents,
- the control of a continuous stirred tank heating system.

All have the characteristics of requiring a minimum of expensive apparatus, being easy to carry out experimentally, being easy to model and to simulate on the computer and providing insight into ChE fundamental processes.

EXAMPLE: TRANSIENT HEATING

THE APPARATUS IS shown in Figure 3. A 400 litre capacity stainless steel stirred pressure vessel is heated with steam, using an external jacket. Cooling is provided by an internal water-cooled coil. Temperatures are recorded continuously as a function of time for the tank contents, and for the inlet and outlet cooling water. The steam jacket pressure is measured and also the flow of cooling water. The students are required to measure the dynamics of heating and cooling the tank contents. Starting at ambient conditions, the tank is heated to the maximum temperature

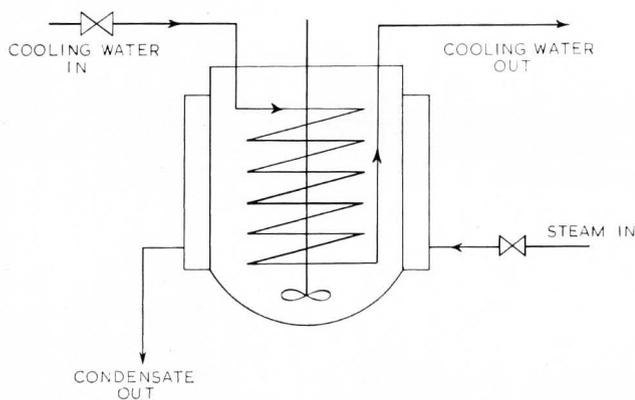


FIG. 3. TRANSIENT HEATING OF A REACTOR VESSEL.

provided by the low pressure steam supply. From this stage, the system is cooled to cooling water temperature. A steady state heat balance is made by comparing the heat supplied by the steam to the heat removed in the cooling water.

A heat balance on the well mixed vessel contents is as follows:—

$$M_w C_w \frac{dT_w}{dt} = Q_w$$

Allowing for the rate of accumulation of heat in the thick vessel walls

$$M_m C_m \frac{dT_m}{dt} = Q_s - Q_w$$

The heat transfer relations determine the heat quantities

$$Q_w = U_w A_w (T_m - T_w)$$

$$Q_s = U_s A_s (T_s - T_m)$$

The steam temperature depends on the steam pressure (saturated steam). The steam pressure depends on the mass of steam in the jacket, the jacket volume, and the jacket temperature. Thus a mass balance is required for the steam jacket.

$$\frac{dM_s}{dt} = F_s - Q_s/\Delta H$$

The term $(Q_s/\Delta H)$ is the condensate rate, and F_s is the inlet mass flow rate given by the relation

$$F_s = K A_v \sqrt{P_o - P_s}$$

where

$$P_s = \frac{M_s R T_s}{V}$$

and

$$T_s = f_{eq}(P_s)$$

Determining the steam pressure involves an algebraic loop between the data in steam tables and the ideal gas law, as shown in the information flow diagram Figure 4.

CONCLUSIONS

A ChE laboratory course based on the modeling and computer simulation of dynamic experimental conditions has been found to have many advantages over the conventional steady state approach in terms of increased interest and motivation on the part of the student. The use of a digital simulation language forms a considerable aid to the learning process in addition to providing a

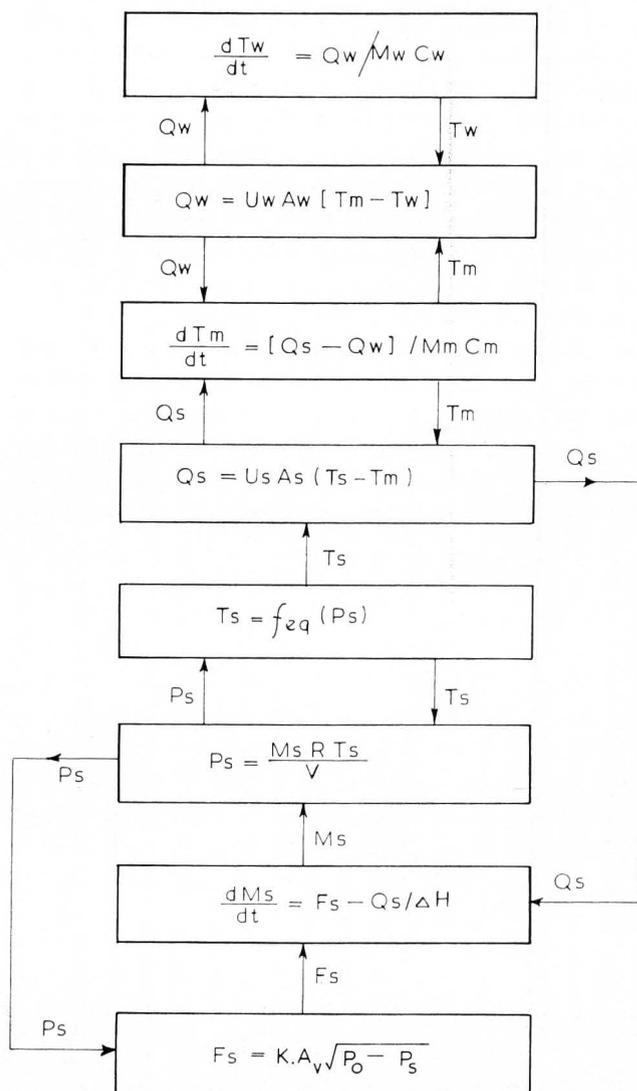


FIG. 4. INFORMATION FLOW DIAGRAM

simple and direct means of solving quite complex problems leaving the student free to concentrate on the actual physical nature of the system. □

ACKNOWLEDGEMENTS

The authors would all like to thank Professors Bourne, Richarz and Rippin for their encouragement and interest during the development of this course. One author (J. Ing-ham) would also like to thank the authorities of the Swiss Federal Institute of Technology and especially Professor J. Bourne for the opportunity to work at the Technisch-Chemisches Laboratorium during the period 1971-1972.

NOMENCLATURE

A_w	Heat transfer area on water side	L^2
A_s	Heat transfer area on steam side	L^2
A_v	Valve fractional opening	
C_w	Heat capacity of water	$L^2T^{-1}\theta^{-1}$
C_m	Heat capacity of metal	$L^2T^{-1}\theta^{-1}$
F_s	Flow rate of steam	MT^{-1}
ΔH	Latent heat of vapourization	L^2T^{-2}
K	Valve coefficient	LT
M_w	Mass of water in vessel	M
M_m	Mass of metal in jacket wall	M
M_s	Mass of steam in jacket	M

BOOK REVIEWS

Continued from page 5.

A chapter on power consumption of mixing impellers reviews some of the theory, gives guidance on measuring power on small scale equipment and then extensively covers the prediction of power consumption for various impellers in large scale equipment both for baffled and unbaffled vessels and Newtonian and non-Newtonian fluids.

In the chapter on heat transfer some modifications to common correlations are presented, including additional geometric parameters. These new forms correlate well the published data for turbulent heat transfer which had previously been correlated with equations having differing exponents. Heat transfer from viscous fluids using anchor or helical ribbon impellers is well covered.

Three chapters deal with flow modeling theory, as well as data for calculating mixing times, and circulation rates continuing the balance between theory and practical design information.

Four chapters are devoted to nonhomogeneous agitation operations: solid-liquid, immiscible liquid contacting, and gas-liquid processing. Quantitative information is presented, but the correlations are not as well defined and substantiated as those for power and heat transfer.

A final chapter is called "Applications" which

P_o	Pressure of steam source	$ML^{-1}T^{-2}$
P_s	Pressure of steam in jacket	$ML^{-1}T^{-2}$
Q_s	Heat transfer rate from steam	ML^2T^{-3}
Q_w	Heat transfer rate at water side	ML^2T^{-3}
R	Gas constant	$ML^2T^{-2}\theta^{-1}$
T_m	Temperature of metal wall	θ
T_s	Temperature of steam	θ
T_w	Water temperature	θ
U_w	Heat transfer coefficient on water side	$MT^{-3}\theta^{-1}$
U_s	Heat transfer coefficient on steam side	$MT^{-3}\theta^{-1}$
V	Steam jacket volume	L^3

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is a qualitative overview of the whole subject of mixing. This chapter is a good summary for developing an understanding of the field of mixing, but is void of any quantitative design information.

While I highly recommend this book, it does have limitations, some of which are acknowledged by the author. For a book titled "Mixing" there is no real discussion of pipeline or static mixing techniques, which is presently one of the most active areas of mixing interest. Mixing of very high viscosity materials, greater than about 1000 poise, is also excluded. Lists of nomenclature are found at the end of each chapter, but they are not all inclusive, and symbols and units are a source of confusion throughout the book. Some of the text reads a little rough, which may be due to translation from Japanese. For those looking for accurate design and scale-up methods for all mixing equipment the book will not completely satisfy the need. Mixing operations are very dependent on geometry of the particular system which makes generalizations difficult. There remains a need for considerable judgment among existing methods and techniques. This book can provide a good source from which to exercise that judgment.

SIMULATION OF THE CARDIOPULMONARY CIRCULATION: An Experiment in Reactor Analysis with Medical Applications

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THE INDICATOR DILUTION technique is a very important diagnostic method for the calculation of cardiac output (i.e. the blood flow rate), cardiopulmonary volumes and mean transit times, as well as for the detection of circulatory diseases and abnormalities [1, 2]. As this technique is based almost exclusively on the principles of chemical reactor analysis, it represents a very suitable experimental topic for students in chemical engineering and bioengineering, and is particularly valid for the growing number of those who are preparing themselves for future medical studies. The experiment described herein has been one of the projects in the senior laboratory courses offered by the Department of Chemical Engineering and Applied Chemistry of Columbia University.

Use of tracers has been a very common method in the study of flow reactors. Internal and exit age distribution functions [3] in chemical reactors are calculated by analyzing the response curve to a tracer input signal. As the heart chambers are analogous to stirred tank reactors [4, 5], the principles of reactor analysis can be employed in the study of the human circulation.

Figure 1 is a simple representation of the heart. Its right chambers are essentially a mixing vessel that pumps blood into the lungs. Since the pulmonary circulation is an extended capillary system, flow occurs with little mixing. The left side of the heart is analogous to the right; it, too, is a mixing chamber whose purpose is to force the

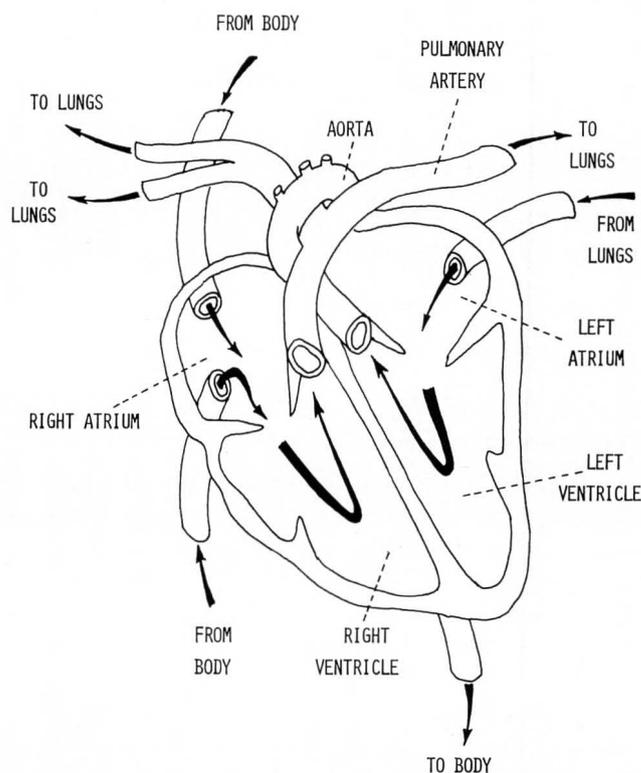


FIGURE 1. Blood flow patterns in the heart chambers.

blood out into the body (systemic circulation). A bolus of indicator (a dye, for example) is injected into one point of the system and the time dependent detection of the tracer is made at a second point. From these data, the volumetric flow rate and the volume of the system between the injection and sampling points can be determined.

Current clinical indicator dilution practice is based upon the Stewart-Hamilton formulation [6] which treats the vessel wherein the tracer is injected as an ideal stirred tank. The indicator is usually a radionuclide such as Tc^{99m} or I^{131} , although dyes are sometimes used. A more suitable tracer for a laboratory experiment is a soluble salt (e.g. KCl) so that continuous conductivity

measurements can be made at appropriate positions within the circulatory reactor model.

THEORY

THERE EXIST TWO types of continuous ideal chemical reactors, the Continuous Flow Stirred Tank Reactor (CFSTR) and the Plug Flow Tubular Reactor (PFTR). The first of these is a vessel in which perfect mixing assures uniform concentration in all parts of the tank; this also accounts for the concentration of the outflow stream being identical to that of the reactor contents. In the absence of chemical reaction, the ideal CFSTR is simply a vessel for perfect mixing of a number of materials.

The ideal PFTR represents the opposite end of the spectrum. It is commonly a tube in which the concentration is uniform at each radial cross section, but with no mixing taking place in the axial direction. The fluid traverses the tube with a flat velocity profile; thus, the necessary and sufficient condition for ideal plug flow is that all flow elements have the same residence times in the reactor. For this reason, in the absence of chemical reaction, the PFTR behaves as a delay function within a flow system.

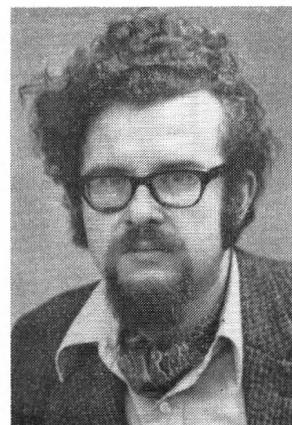
The response of ideal reactors to different inputs is extensively covered in the literature [3, 7]. When an impulse injection of a tracer is made into an ideal CFSTR, the concentration in the effluent decays exponentially. Then, the flow rate, F , is given by the formula

$$F = \frac{I}{\int_0^{\infty} C(t) dt}, \quad (1)$$

where I is the amount of tracer injected and $C(t)$ is the time-varying concentration of indicator in the outflow stream. The denominator of this expression represents the total area under the concentration-time curve and can be evaluated analytically, graphically, or numerically [8, 9].

The mean transit time, \bar{t} , of tracer in a vessel

As the heart chambers are analogous to stirred tank reactors, the principles of reactor analysis can be employed in the study of human circulation.



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is the average of the individual residence times of all indicator particles. Thus,

$$\bar{t} = \frac{\int_0^{\infty} t \cdot C(t) dt}{\int_0^{\infty} C(t) dt}. \quad (2)$$

Once the flow rate and mean residence time in a vessel have been determined, its volume is found by multiplying these two quantities:

$$V = F \cdot \bar{t} \quad (3)$$

To apply this analysis to the study of the human circulation, a rapid injection of tracer is made into the right heart. This would yield the arterial dilution curve of Figure 2a or the precordial dilution curve of Figure 2b, depending upon the method of sampling. If samples are obtained directly from an artery subsequent to the right heart, indicator concentration will rise sharply after injection and then decrease as the tracer is washed away by the blood flow yielding

the general shape seen in Figure 2a. If the injection is practically instantaneous and the right heart operates as a CFSTR, then, on the basis of the above analysis of ideal reactors, the upstroke of the arterial dilution curve should be vertical and the decay exponential (see e.g. Figure 4a).

When a radioisotopic indicator is used, the precordial dilution shape of Figure 2b is obtained.

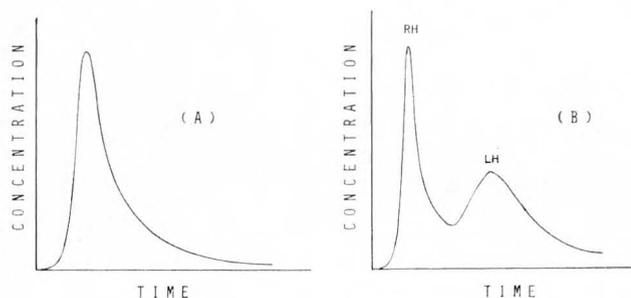


FIGURE 2. Generalized arterial (a) and precordial (b) dilution curves. RH: right heart peak; LH: left heart peak.

Again, a right heart peak and decay are seen immediately after injection. However, since the left heart is also within the field of the gamma ray detector, a second peak will appear as the radioactive particles enter the left heart after having traversed the pulmonary circulation. This peak will be lower than the right heart peak because of the substantial dilution of tracer during its flow through the cardiopulmonary circulation, and will also decay as the tracer particles enter the systemic blood pool.

Theoretical analyses of the indicator dilution technique are described in detail in the literature [10, 11] and the applicability of the previously discussed chemical reactor theory to indicator dilution practice [12] and to subsequent investigation of the pulmonary circulation [13] has been analyzed. Application of chemical reactor analysis requires the following assumptions:

- The tracer used should have rheological properties similar to those of whole blood.
- The circulation should contain no stagnant pools [14].
- The heart chambers should function as CFSTR's [4, 5].
- Impulse injections must be used [15].

The above references state and discuss the validity of their respective assumptions.

EXPERIMENTAL

THE GENERAL LAYOUT of the apparatus is shown in Figure 3. An open system is preferable to a closed one from the experimental point of view because it does not require flushing out of the

indicator after each run, or subtraction of the initial tracer concentration. A further advantage of this arrangement is that the use of a pump is not necessary for fluid flow.

Continuous Flow Stirred Tank Reactors are used to model the two heart chambers [4, 5]. These should ideally be made of a transparent plastic (e.g. poly(methyl methacrylate)) to permit close observation of fluid flow through them. Their shape should be cylindrical to eliminate stagnant pockets, and their diameter and height should be of comparable dimensions. To maximize mixing, the inflow and outflow tubes should be placed tangentially to the curved cylinder surface at its bottom and top, respectively. The volume of the right and left heart models should be the same as in the average human circulatory system (130 to 150 cc).

The pulmonary circulation is also modelled by a transparent cylinder of the same material as the right and left heart. Lovinger [13] has shown that pulmonary circulation behaves essentially as a chemical reactor containing ca. 75% plug flow regions and 25% mixing ones. This is consistent with the actual physiological system because it is expected that practically no mixing will be taking place in the capillaries which would instead provide most of the delay during pulmonary flow; however, substantial mixing should be taking place in the large arteries and veins and at all junctions. In practice, it was found that a long cylinder, ca. 1.5" in diameter and 14" long, will have the average pulmonary volume (400 cc) and provide the above percentages of mixing and plug flow. Mixing will obviously be concentrated at the entrance and exit regions, with plug flow in between. A closer approximation to plug flow is obtained when this cylinder is placed vertically since

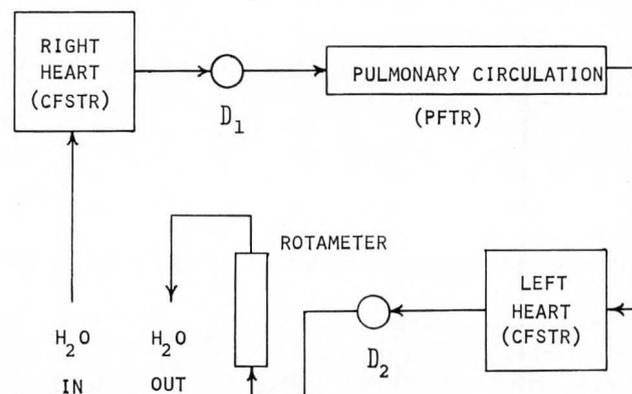


FIGURE 3. Flow diagram of the experimental apparatus. CFSTR: Continuous Flow Stirred Tank Reactor; PFTR: Plug Flow Tubular Reactor.

If the injection is practically instantaneous and the right heart operates as a CFSTR, then, on the basis of the above analysis of ideal reactors, the upstroke of the arterial dilution curve should be vertical and the decay exponential.

the force of gravity will tend to flatten the velocity profile.

These three vessels are connected in series by use of flexible transparent tubing (e.g. soft poly (vinyl chloride)). The total length of connective tubing should be minimized, and the volume of the segments between the pulmonary circulation and the two heart chambers should be counted as part of the pulmonary blood volume.

The circulating fluid used is ordinary tap water, whose rheological properties are similar to those of blood. Its flow rate is controlled by a needle valve and measured by a rotameter. The indicator is 4N KCl, although lower concentrations can be used if the chart recorder has a sensitivity greater than 10 mV full scale. Injections are made by use of a syringe attached to a valve and needle. The needles are actually put permanently through the walls of the tubing at appropriate positions ahead of the right and left heart. They are held in place by use of silicone rubber and contain stopcocks which are ordinarily closed so that no water escapes through them due to the flow pressure.

Two conductivity cells are installed in-line after the right and left heart vessels (points D_1 and D_2 in Figure 3) to monitor the concentration of KCl. Each consists of two platinized rods, 0.5 mm in diameter, extending 2 mm into the stream, and is connected through a switch to a specific conductance meter (Beckman Instruments, Inc.) having a scale of 50 micromhos/cm. This in turn is attached to a chart recorder (Bausch & Lomb, Inc.) which provides continuous curves of d.c. voltage versus time. To minimize the amount of tracer injected, as low a scale as possible of voltage should be used (preferably less than 10 mV full scale). Chart speed can be varied; the speed used in our experiments is 5 inches/min.

EXPERIMENTAL PROCEDURE

ONCE THE APPARATUS is set up and working properly, the actual experimental pro-

cedure should require no more than one laboratory period of five hours by a team of at least two students or the equivalent. The rotameter is calibrated first by use of a volumetric cylinder and a timer; a calibration curve of rotameter reading versus flow rate in lit/min should be constructed to cover the entire spectrum of cardiac outputs obtainable, i.e. from 1 lit/min to 10 lit/min. Next, a calibration curve relating recorder voltage to indicator concentration should be constructed by use of standard solutions of KCl.

After these two curves are obtained, the actual indicator dilution procedure can take place by establishing a constant flow rate and injecting a minimum (preferably less than 3 cc) of KCl solution as rapidly as possible. Injections should be made ahead of each vessel (equivalent to venous injection in humans) or directly into the right

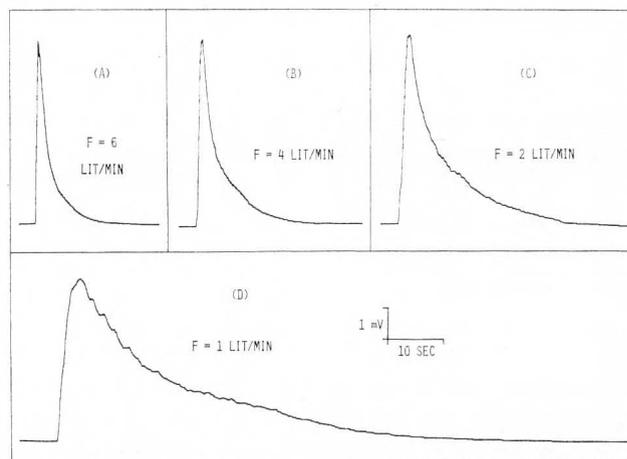


FIGURE 4. Indicator dilution curves obtained for various flow rates from the circulatory model. Tracer injected into the right heart by use of a catheter and detected at point D_1 in Figure 3.

heart by use of a catheter. Either of the two conductivity cells D_1 and D_2 should be attached to the recorder, so that arterial dilution curves similar to those shown in Figure 4 will then be obtained. For actual calculations, it is best to follow the usual medical practice by injecting directly into the right heart and sampling at D_1 . The same procedure should be repeated at different flow rates and with variation of injection sites and types. From these data, one is able to investigate the effect of flow rate, injection duration, and injection and sampling positions upon the accuracy of calculations.

Calculations: By use of indicator dilution curves obtained as above, and of Equation (1),

the cardiac output can be calculated and compared to the actual flow rate given by the rotameter calibration curve. Similarly, mean residence times in circulatory segments can be determined from Equation (2). Equation (3) can then be employed in the calculation of the various volumes between injection and detection points which should be compared to the actual volumes in the circulatory model. Means and standard deviations of cardiac output and right heart volumes might also be determined for the runs at each flow rate. Finally, the downslopes of the dilution curves obtained should be plotted in semilogarithmic coordinates to check linearity at the various flow rates.

RESULTS AND DISCUSSION

WHEN FLOW RATES between 3 and 6 lit/min are employed, all parameters should be computed to an accuracy of better than 5%, provided that injections were made rapidly directly into the right heart. Obviously, slower injections or those that were made in the tubing ahead of the above vessels will cause higher deviations from the true values of cardiac output because the impulse injection and the ideal mixing assumptions will no longer be completely valid. The same tendency in the results will also be observed in lower flow rates since the turbulence created in the two heart vessels will not be adequate to assure perfect mixing. This may also result in the formation of stagnant pockets which will provide erroneously low values for the heart volumes. Very high flow rates (above 7 lit/min) imply minimal tracer residence times in the heart chambers; thus, if the response of the conductance meter or chart recorder is not sufficiently fast, inaccuracies may again be obtained. The mixing effects in the various vessels can be qualitatively observed if a colored dye (e.g. Rhodamine) is added to the KCl solution.

A significant measure of the rapidity of injection and of the degree of mixing within the heart chambers is provided by the shape of the arterial dilution curves. At the higher flow rates (above 3 lit/min) the initial upstroke is almost vertical and the downstroke approaches very closely a theoretical exponential decay (see Figures 4a and 4b). Deviations from this behavior are seen at lower cardiac outputs (Figures 4c and 4d). The students will be able to see this tendency more descriptively if the downstrokes of the dilution curve at various flow rates are replotted in semilogarithmic coordinates, in which an exponential decay appears

as a straight line. Consequently, least squares curve fitting procedures can be used to test deviations from this behavior.

The nature of these calculations (i.e. repeated integrations and least squares curve fittings) makes use of computer programming particularly attractive. Subroutines for these numerical computations are available in the literature [8, 9] and could be used by the students, who would only have to provide the values of the dependent and independent variables when calling up the appropriate subprogram. A complete computer program that calculates cardiac output, mean residence times and circulatory volumes has been reported in the literature [16]. Composition of such a complete computer program may also be undertaken by a team of students as a term project.

Another suitable project may involve the investigation and explanation of the effects of circulatory diseases and abnormalities (e.g. arteriovenous shunts, mitral and aortic stenoses, "blue baby disease") on the indicator dilution curves. In most actual medical cases, these anomalies are detected and quantified by use of precisely this method, and numerous references are available in the literature [e.g. 12, 17]. These circulatory abnormalities can be very easily studied on the model by simply adding flow connections between the appropriate points for each case.

ACKNOWLEDGEMENT

The authors wish to thank Professor Elmer L. Gaden, Jr., and Mr. Frank Lech for their part in the design of the experiment. □

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(Continued on page 39.)

A SIMPLE, INSTRUCTIVE SOLID STATE DIFFUSION EXPERIMENT FOR USE IN TEACHING LABORATORIES

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THE PROCESS OF ATOMIC diffusion in solids is fundamental to many basic processes considered by the materials scientist or engineer. Hence an instructional unit in diffusion is almost mandatory in the education of an engineer who wishes to have even the most rudimentary knowledge of the important basic materials phenomena. However, in attempting to explain the physical significance of the phenomenological equations describing diffusion such as Fick's Laws, many educators have difficulty in presenting tangible evidence of their applicability to relevant materials. It is one thing to describe diffusion mathematically, quite another to "see" the process taking place in a laboratory experiment which illustrates the mathematical description.

In this note we wish to describe an experiment which was developed for use in the undergraduate curriculum in Ceramic Engineering at the University of Washington. The experiment is simple to conduct, the results are easily obtained and it describes diffusion in a common high temperature material, magnesium oxide.

The experiment is based on similar experiments conducted by Zaplatynsky (1) involving cobaltous ion diffusion in single crystal magnesium oxide. The basic principle involved in the determination of the diffusion coefficients and activation energies for the system is the measurement of the rate at which a surface of fixed concentration moves away from a reference interface. The advantages of using this system are: (1) the

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materials are easily obtainable, (2) the surface of fixed concentration is defined by a sharp color change in the crystal, (3) diffusion coefficients are such that reasonable penetrations are possible at temperatures available in simple laboratory furnaces and for reasonably short diffusion times, and (4) the vapor pressure of cobaltous oxide is such that nearly perfect contact is achieved at the initial interface.

PROCEDURE

THE MATERIALS USED in the experiment are easily obtainable. Small magnesium oxide crystals may be obtained for little or no cost from normal suppliers*. The purity is not determined, nor is it felt necessary since the object was to demonstrate the validity of the diffusion equations, not to investigate the effects of impurities on diffusion rates. The cobalt oxide is standard technical grade available from any chemical supply house.

The experimental procedure followed is outlined below. The MgO crystals are cleaved to an approximate size of 10x4x4 mm. A corner is ground off each crystal for orientation purposes

*For example, Norton Co., Worcester, Mass.

and the two short dimensions were measured using a micrometer stage microscope. The crystals are then packed in the CoO powder, which has been dried at 100°C for 24 hrs, in small Al₂O₃ crucibles. These are in turn placed in small fire-clay crucibles, much as eggs in egg cups, and covered with a single alumina lid. This double crucible technique is necessary because the high vapor pressure of CoO at elevated temperatures results in the vapor drifting out of the inner container and down the sides. If the second crucible is not present, the furnace will be contaminated. Using this simple technique, the furnace refractories show no sign of the characteristic cobalt blue contamination.

The crucibles are placed in a silicon-carbide-resistance furnace and heated at the desired temperature. At selected times a crucible is withdrawn and the diffusion anneal continued on those remaining. Upon cooling after removal from the furnace, the lump of sintered cobalt oxide is removed, cracked open gently with a hammer and the crystals removed. Three thin sections, about one millimeter thick, are then cleaved transverse to the long dimension of the crystals at approximately the mid-length. These are cemented to microscope slides with epoxy resin. The sections are examined microscopically and the two dimensions of the colorless MgO central portions measured. Care is taken during cleaving and mounting to preserve the orientation, so the dimensions may be matched with corresponding dimensions of the original crystal. The depth of penetration, x , is given by

$$x = (w_0 - w_1)/2 \quad \text{or} \quad (d_0 - d_1)/2$$

where w_0 = original width of crystal
 w_1 = corresponding width of colorless crystal after anneal
 d_0 = original depth of crystal
 d_1 = corresponding dimension of colorless crystal after anneal

Thus for two crystals at any one time and temperature a total of twelve measurements may be made of x .

ANALYSIS

FOR THIS GEOMETRY, where the penetration depth is small compared with the size of the specimen and is measured by the distance from the original interface to the region of rapid color change, the solution to Fick's Second Law for one dimensional diffusion into an infinite medium with

constant surface concentration is appropriate. This solution is

$$C = C_s \left(1 - \operatorname{erf} \frac{x}{2\sqrt{Dt}} \right) \quad 1$$

where the error function, $\operatorname{erf} = \frac{2}{\sqrt{\pi}} \int_0^{\frac{x}{2\sqrt{Dt}}} e^{-z^2} dz$

and C_s = constant surface concentration
 C = concentration at surface of rapid color change
 x = penetration distance
 D = diffusion coefficient
 t = time

From equation (1)

$$\frac{x}{2\sqrt{Dt}} = \operatorname{erf}^{-1} \left(1 - \frac{C}{C_s} \right)$$

where erf^{-1} is the inverse error function.

If the surface concentration and the concentration at the color change surface are known, the relationship between x and t is determined by

It is one thing to describe diffusion mathematically, quite another to "see" the process taking place in a laboratory experiment which illustrates the mathematical description.

consulting a table of error functions (2) and is of the form

$$x^2 = kDt$$

where $k = 4 \operatorname{erf}^{-1} \left(1 - \frac{C}{C_s} \right)^2$.

Zaplatynsky, in his work on this system, assumed a value of four for k regardless of the surface concentration. He found as a result that the apparent diffusion coefficient for cobalt diffusion in MgO was an order of magnitude lower if a surface concentration of 30 m/o CoO was imposed rather than 100 m/o. The difficulty in assigning a value to k arises from not knowing what the concentration of CoO is at the color change surface. On the basis of Zaplatynsky's chemical analysis of

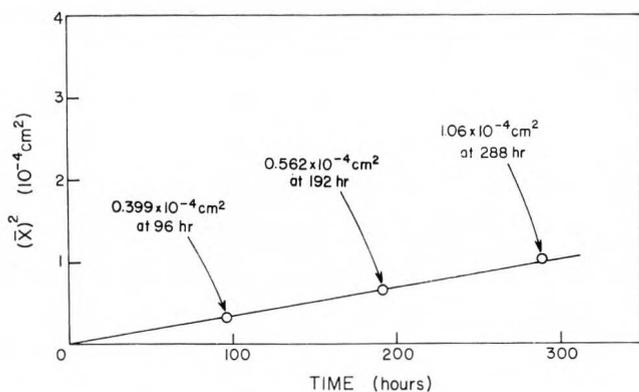


FIGURE 1. Plot of Average Penetration Depth Squared, $(\bar{X})^2$, as a Function of Time for Diffusion of Co^{++} into MgO at 1250°C .

his specimens together with his measurements of penetration depth it would appear that this concentration is nearly 60 m/o CoO ; however, this is impossible since he had a color change surface when the surface concentration was held at only 30 m/o. If one assumes a value of, say, 20 m/o, then a value of k may be obtained for each value of the surface concentration used. For the surface concentration used by Zaplatynsky, the values are:

Surface Concentration	k
100 m/o CoO	3.6
30 m/o CoO	1.2

Recalculation of Zaplatynsky's diffusion coefficients for Co in MgO yields values which are much more nearly equal for the two conditions of surface concentration.

On this basis all that is required for the determination of a diffusion coefficient is a series of penetration depths, x , and corresponding times, t . A plot of x^2 as a function of t should be a straight line of slope kD . By plotting $\ln D$ against corresponding values of reciprocal absolute temperature, for diffusion coefficients measured at various temperatures, activation energies, E_a , and diffusivity constants, D_0 , may be determined from the slope and intercept.

RESULTS OF TRIAL RUNS

AS A TRIAL CASE, six crystals were run under the procedure outlined above at 1250°C for three times, 96, 192 and 288 hours. The results of the tests are shown in Figure 1. Each point represents an average of twelve independent measurements of the penetration depth, two measurements on each of three sections from two different crystals. The diffusion coefficient at 1250°C calculated using a value of $k = 3.6$ was 2.6×10^{-11}

cm^2/sec . Zaplatynsky's data yield a diffusion coefficient at the same temperature of $3.9 \times 10^{-11} \text{ cm}^2/\text{sec}$. This result suggests that whatever the shortcomings of the analysis, the results of the experiment are reproducible.

USE OF THE EXPERIMENT

THE LONG TIMES INVOLVED in the diffusion anneals probably require that specimens be prepared before the students are introduced to the experiment. In our program, the specimens are given to the students mounted on microscope slides and ready for measurement (Fig. 2). A good description and/or demonstration of the preparation of the specimens is given, together with some background information on the analysis of the data. The students then measure the specimens, plot the data and derive values for the diffusion coefficients, activation energies and diffusivity constants.

The laboratory report written by the student requires a description of the procedure, presentation of data and an evaluation of the results. The student is led to examine certain aspects of the experiment by including in the syllabus for the experiment a few questions which he should discuss.

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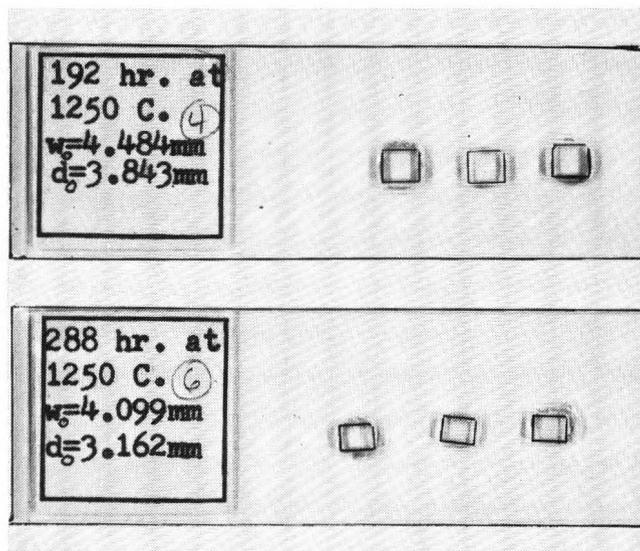
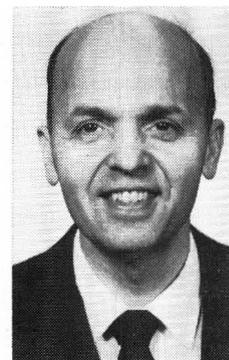


FIGURE 2. MgO-Co^{++} Diffusion Specimens Prepared for Student Use. (Note that temperature, time duration of diffusion anneal, and w_0 and d_0 are marked on each slide.)

Laboratory Demonstration

TEMPERATURE APPROACH IN COUNTER-FLOW HEAT EXCHANGERS

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W. Henry Tucker received his B.S. in Ch.E. degree from The University of Virginia, 1942, and the degrees of S.M. and Sc.D. from M.I.T. After industrial experience with Servel, Inc., he taught at Purdue University for 16 years. In 1969 he became Chairman of Chemical Engineering at Tri-State University. He has research interests in heat and mass transfer with particular emphasis on absorption refrigeration. He has served as Advisor to Cheng Kung University, Taiwan, and in 1969 was awarded the first Winston Churchill Traveling Fellowship to Great Britain. In 1959 he spent a sabbatical at the Swiss Federal Institute of Technology.

SOMEWHERE ALONG the road which leads to the making of a B.S. chemical engineer who is able to understand heat transfer rate processes, we should teach him an understanding of the "pinch-point" in countercurrent heat exchangers (the point along the length of the exchanger where the temperatures of the two streams approach each other). Sometimes it is at the hot end, sometimes at the cold, and frequently, somewhere inside when there is a change of phase giving a change in the stream heat capacity. Reference 1 discusses temperature approach in a process for producing pipeline gas from coal where energy is a major cost item. The classical text-

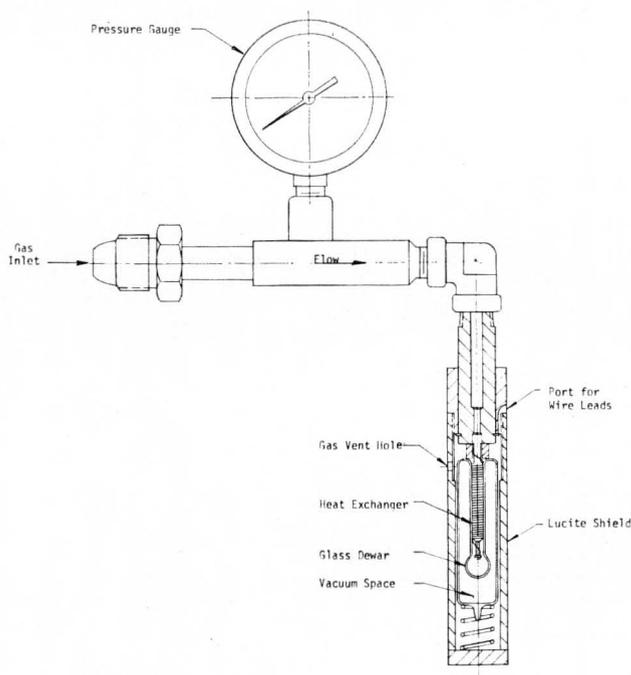


FIGURE 1. Break-away of JT Refrigeration Demonstrator.

book, *Industrial Stoichiometry*, Lewis, Radasch, and Lewis, [2] thought the subject important enough to devote all of chapter 3 to it. New books tend to teach energy balances to the sophomore without relation to the heat exchanger, and transport processes follow in the junior year without reference to the equilibrium case.

It was the purchase of a Joule-Thomson Refrigeration Demonstrator from Air Products and Chemicals, Inc. [3] that gave the author the feeling that here would be a classical way of demonstrating this pinch-point phenomenon and how it could shift from one end of the heat exchanger to the other. This device is shown in Fig. 1. High pressure nitrogen from a cylinder (at say, 200 atm pressure), flows through the inside of a heat exchanger and expands into a glass dewar at a pressure approaching atmospheric. This is the usual way of producing a small percentage of liquid from the incoming gas stream. But this particular device has no separate exit for product

TABLE I
Temperature—Specific Enthalpy Data from Fig. 2

TEMP. °K	h (1ATM) cal/mol	h (200 ATM) cal/mol
320	3046	2850
260	2630	2320
200	2210	1700
140	1790	890
77	1310 sat'd vapor	390
77	0 sat'd liq.	130

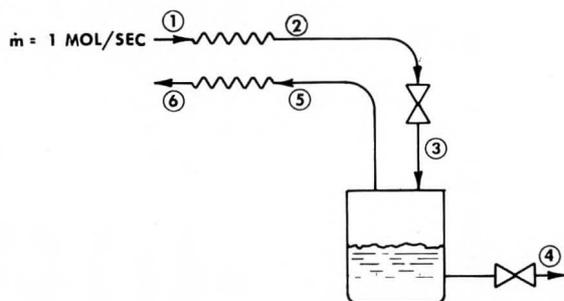
SAT'D LIQUID SPECIFIC ENTHALPY DATA

Perry's, 4 ed. p. 3-180
 115K - 534 cal/mol
 100 - 326
 80 - 39

liquid nitrogen, so that the entire stream flows back across the heat exchanger to the exhaust port. It turns out that, instead of the usual 5% or so of liquid product, the bulb in the dewar is practically 100% liquid, which, of course, re-evaporates in its passage back through the heat exchanger.

Since the standard J-T expansion is well documented in thermodynamics, no separate experiment is needed for it here. What this article will do is to compare the heat exchanger temperature profile for the standard J-T with liquid product

CASE I - J-T WITH LIQUID PRODUCT



CASE II - J-T WITH TOTAL RECYCLE OF PRODUCT

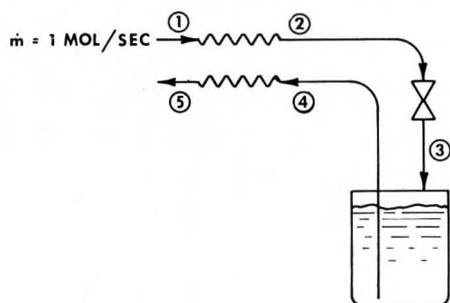


FIGURE 2. Diagrams of the two cases being compared.

(Case I) and that of the demonstrator in Fig. 1 (Case II) to show how the pinch-point shifts. See Fig. 2 for the process diagrams.

In order to obtain a temperature profile in a heat exchanger, one needs heat capacity data. Fig. 3 gives temperature vs. specific enthalpy data for nitrogen, and data for the two pressures selected, 1 atm and 200 atm, are plotted in Fig. 4, and the data are tabulated in Table I. The 1 atm data show a change of phase from gas to liquid at 77K, while the 200 atm data being above the critical pressure show no such discontinuity.

For Case I, we consider the J-T expansion giving a liquid product. To determine the percent of the feed that is liquified, one customarily wraps an energy balance around the whole system, cutting streams 1, 4, and 6 in Fig. 2. The calculations

Somewhere along the road which leads to the making of a B.S. ChE who is able to understand heat transfer rate processes, we should teach him an understanding of the "pinch-point in countercurrent heat exchangers.

in Table II indicate that 8.25% of the feed would be liquified, assuming temperature equilibrium between streams 1 and 6—or the assumption of an infinite area heat exchanger. Assuming instead a 25F pinch at the warm end, the product drops to a mere 2.2% of the feed stream.

The student usually accepts this calculation without thinking the matter through. It, of course, turns out to be correct. But the basic assumption involved should be checked—that the thermal equilibrium, or "pinch" in the finite area case, occurs at the warm end of the exchanger. This is true because the heat capacity of the high pressure stream is in general greater than that of the low pressure stream. What is important is the total heat capacity of the streams. The heat capacity of the low pressure stream is even lower when the product withdrawal causes the exit gas stream to have a lower mass flow rate than that of the high pressure stream.

Fig. 5 shows the temperature profiles for the cases of zero and 25K temperature differences at the warm end. It is a plot not of specific enthalpy but of total stream enthalpy, still keeping the high pressure stream on a 1 mol/sec. basis. The low pressure stream is based first on a 0.9175 mol/sec.

TABLE II
Energy Balances for Case I, Fig. 2

0° Δt - INFINITE AREA HEAT EXCHANGER

$$\begin{aligned} h_6 &= 2915 \text{ cal/mol}; t = 300\text{K} \\ h_4 &= 0 & 77\text{K} \\ h_1 &= 2675 & 300\text{K} \end{aligned}$$

$$\begin{aligned} h_1 \times 1 \text{ mol/sec.} &= h_4(x) + h_6(1-x) \\ x &= .0825 \text{ mol liq/mol feed.} \end{aligned}$$

25° Δt

$$\begin{aligned} h_4 &= 0 & T = 77\text{K} \\ h_6 &= 2740 & 275\text{K} \\ h_1 &= 2675 & 300\text{K} \end{aligned}$$

$$\begin{aligned} h_1 \times 1 \text{ mol/sec.} &= h_4(x) + h_6(1-x) \\ x &= 0.0225 \text{ mol liq/mol feed.} \end{aligned}$$

35° Δt

$$\begin{aligned} h_4 &= 0 & T = 77\text{K} & H_1 \times 1 = h_4x + h_6(1-x) \\ h_1 &= 2675 & 300\text{K} & \\ h_6 &= 2675 & 265\text{K} & x = 0, \text{ no product} \end{aligned}$$

TOTAL STREAM ENTHALPY—1 ATM STREAM

T	h	H 0.9175 mol/sec.	H 0.9775 mol/sec.
320	3046	2790	2970
260	2630	2410	2570
200	2210	2025	2155
140	1790	1640	1750
77	1310	1200	1280

basis for the zero temperature difference and then on a 0.978 mol/sec. basis for the 25K difference, in accordance with the calculations on Table II. As these curves are not positioned properly at the warm end in relation to the 300K assumed feed temperature, one bodily moves the curves over to the dotted line positions—quite a small correction but this is just fortitious. Usually the displacement is greater. The reason the two curves can be moved horizontally with respect to each other is that in a heat exchanger which is assumed to be well insulated, the ΔH change in each stream is equal, so that only relative enthalpies are important. Temperatures at the cold end of the heat exchanger for the infinite area and for the finite area are determined by dashed lines A and B, fixed by the enthalpy of the saturated vapor leaving the separator at 77K.

One can continue the calculations on Table II for the case of a 35K temperature difference. At this selected condition, the product rate turns out to be zero, indicating the extreme importance in this process of having a very efficient heat exchanger. (This is the story of the cryogenic industry).

Now we can employ the demonstrator shown in Fig. 1 which by design allows no liquid product. We can conclude from the third calculation on Table I that we will now have a 35K Δt regardless of how large the heat exchanger is (in Fig. 2, Case II, H₁ = H₅). This is an interesting twist, since the warm end Δt can no longer respond to the area of the heat exchanger. One might inquire how this can be. By now, it might be obvious that if the temperatures are fixed at the warm end of the exchanger, the pinch temperature difference, which depends on the amount of area, must lie either inside the exchanger or at the cold end. The solution can be clearly seen on Fig. 4. This plot of specific enthalpy versus temperature is also the total enthalpy if each of the two streams is assumed to have a flow rate of 1 mol/sec. (no product withdrawal). The 35K Δt is shown at the warm end. If one proceeds to the cold end, one spots a zero Δt at about 93% liquid. Actually, when one runs the demonstrator, the product in the dewar collector seems closer to 100% liquid. Since the data on Fig. 3 at the 200 atm pressure are subject to considerable error at the low temperature end, the demonstrator can give a check of this accuracy even if its area is not infinite. When heat exchangers are not infinite, then the

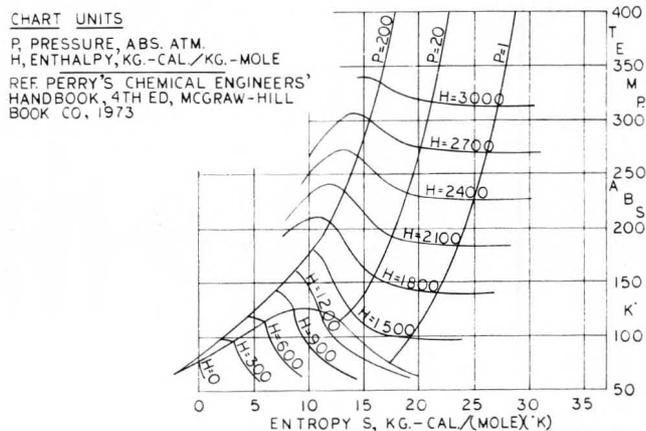
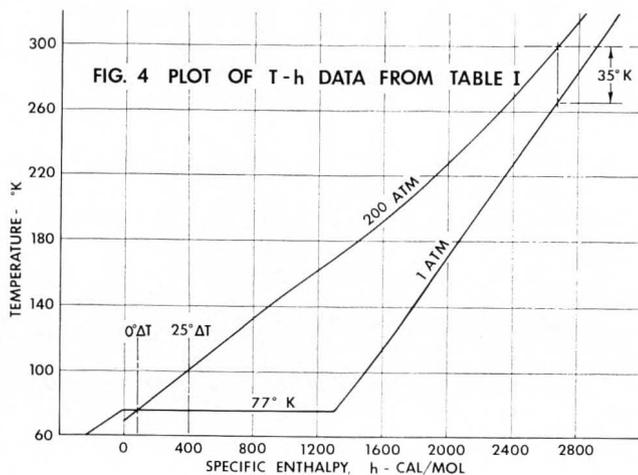


FIG. 3 THERMODYNAMIC CHART FOR NITROGEN



cold end temperatures move to the right on Fig. 4, with the 25K case being shown. Interestingly, if the area is further decreased to give more than a 35K difference, then the minimum Δt switches back to the warm end.

The curves on Fig. 4 also should indicate to the student that to size such a heat exchanger, one must break it up into the evaporating portion and the heating portion to allow the use of log-mean temperature differences, since the stream heat capacity abruptly changes. Actually, one must also estimate the film coefficients, as these are different in the two sections, and constant film coefficients, as well as heat capacities, are assumed when the log-mean relationship is derived. With no phase change, but with non-linear cooling curves (variable heat capacity), one should size a heat exchanger by point-to-point integration rather than the use of a log-mean driving force.

CONCLUSIONS

THE GRADUATING chemical engineer should go out on the job with a clear understanding of the thermal equilibrium case in heat exchangers (for infinite areas), for elegant heat transfer theory and correlations are useless if the basic equilibrium case is not even understood.

The use of the J-T Demonstrator is considered a classical way of showing the floating nature of the pinch-point, which shows up in many heat exchangers encountered on the job, when changes of phase or flow rates are encountered. □

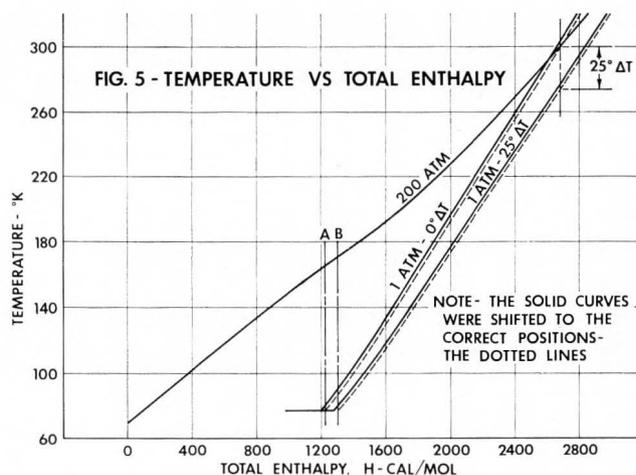
ACKNOWLEDGEMENT

I wish to thank Mr. Robert B. Currie, Principal Development Engineer, Air Products and

Chemicals, Incorporated, for reviewing this paper. He was responsible for the excellent hardware design on the demonstrator.

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Continued from page 32.

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Laboratory Demonstration

COMBUSTION PROJECT: EXPLOSIVE LIMITS

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FOR SEVERAL YEARS an apparatus built according to a description by G. W. Jones [1] has been used by freshman engineering students taking the combustion option in the Department of Chemical Engineering at the University of Toronto, to study the explosive limits of a typical hydrocarbon, as well as a number of basic physical chemistry principles associated with the measurement. It was felt that a modification of the apparatus to make it suitable for demonstration purposes using a "hands-on" approach was desirable. The following criteria for such a design were then established:

- It should be capable of illustrating certain principles (e.g. existence of explosive limits, the vapour-pressure temperature relationship, relative rates of flame propagation, approach to equilibrium).

- It should be simple to operate, requiring only the pushing of buttons, and observation of the effects.

- It should be safe when operated by entirely unskilled people, including children at grade school level.

- It should yield reproducible results without requiring the intervention of an operator.

- It should be essentially self-explanatory.

- The effects should be sufficiently impressive to attract students to the apparatus and to stimulate them to raise further questions and perhaps try further experiments in this field.

- The unit should be essentially portable and yet heavy enough so that it could not readily be removed from any location in which it was set up.

The design to be described here apparently satisfies these criteria. It is hoped that the description will serve to point out the problems and the solutions associated with the re-design of a relatively simple laboratory-scale apparatus to conform to the rather more stringent criteria of a demonstration unit.

DEMONSTRATION UNIT

A DIAGRAM OF SOME of the features of the design of the demonstration unit as finally adopted is shown in Figure 1. The vapour generator and combustion tube combination is made of Pyrex glass and consists of a lower reservoir for the fluid under test, 75 mm long and 25 mm in diameter, which sits in the heated block at the test temperature, and an upper separately heated combustion chamber, 150 mm long and 30 mm in diameter. A glass tube entering the reservoir near the top extends to a position close to the bottom of the reservoir and serves to lead air pumped by a fish-tank aerator at the rear of the unit through a tube partially packed with molecular sieve 5A and restricted at the end, through the test fluid and into the combustion chamber.

The air will pick up a proportion of the vapour

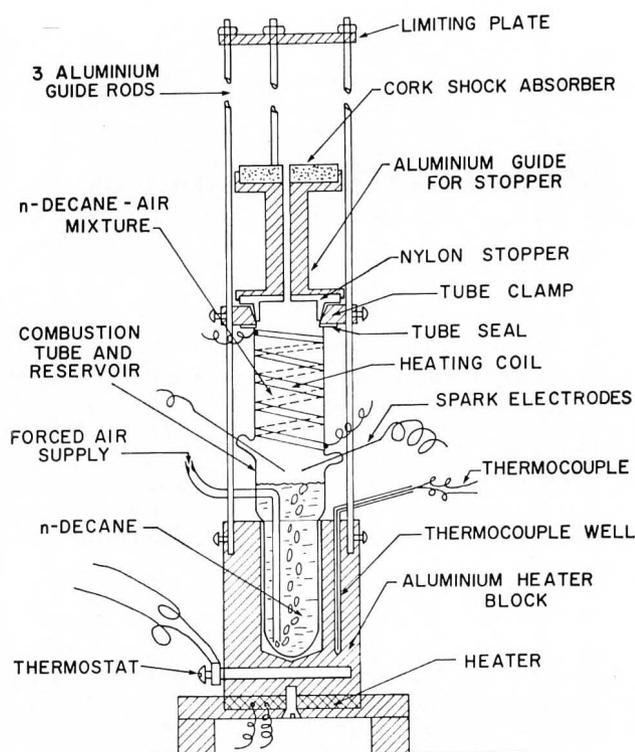


FIGURE 1. Explosive Limits Apparatus.



Professor Sandler received his B.A.Sc. and M.A.Sc. from the University of Toronto. His principal research interest has been in kinetics and mechanism of the oxidation, decomposition, ignition and detonation of fuel vapours and gases as well as of the associated instrumental methods of chemical analysis. After ten years with Defense Research Board of Canada as a Principal Scientific Research Officer on combustion research, he joined the staff of the Department of Chemical Engineering, University of Toronto. Besides his teaching and research work, Professor Sandler is an active consultant on combustion and analytical matters with Chemical Engineering Research Consultants Ltd. He has also been very active in the Chemical Institute of Canada, as chairman of the Toronto Section, as Councillor "A" of the national body, as a tour speaker and as organizer and chairman of the first three Toronto Symposia on Gas Chromatography. He is presently a Fellow of the Chemical Institute of Canada.

of the test fluid which will depend on its vapour pressure at the test temperature and the degree to which equilibration of the air with the fluid is allowed to occur. With the relatively low air flow rate used and after passage of air for at least 30 seconds, a steady state condition is set up which is not far from the equilibrium state. Hence, a vapour pressure-temperature curve for the test fluid (in this case, n-decane) with associated vapour-air composition scales as in Figure 2 can be used to estimate the mixture strength corresponding to operation at any test temperature, as read on a pyrometer. An iron-constantan thermocouple imbedded in the heater block provides the impulse for this reading. The heater for the block is a 300 watt element in its base controlled to within $\pm 0.5^\circ\text{C}$ by a thermostat within the block.

An auxiliary heater coil is necessary to prevent condensation of the vapour in the combustion chamber by maintaining it at or slightly above the test temperature. This less critical temperature is maintained constantly by providing an appropriate voltage from a small transformer to the auxiliary heater of each unit.

After creating the desired mixture of fuel vapour and air, a spark is passed across a 1/4-inch gap between two platinum electrodes located in the lower part of the combustion chamber. The liquid level in the reservoir is usually about 1/2 inch below the electrodes. However, the actual position of the liquid with respect to the electrodes is not critical and the unit may be operated for several days before make-up liquid is required.

Flame propagation is signalled in a number of ways. When the lights are turned off, it is possible to see a flame, initially generated at the electrodes, actually propagated through the mixture if it has a composition somewhere within the explosive limits. In addition, the pressure generated by the

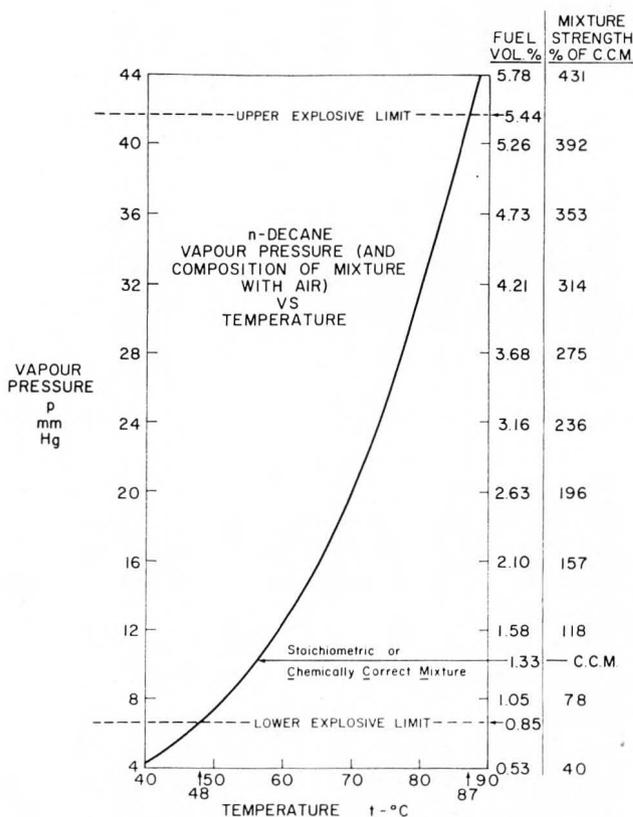


FIGURE 2. Vapor Pressure Plot.

expanding gaseous products of the combustion may be sufficient to lift the Nylon or Teflon stopper off the combustion tube and raise the aluminum guide holding this stopper to some level above its rest position. If the explosion is sufficiently vigorous, that is, if the flame velocity is sufficiently great, this guide will travel all the way up to strike the upper limiting plate. A cork shock absorber is incorporated into the upper end of this guide for the purpose. Subsequently, the guide

returns to its rest position and, *if properly designed*, seats itself snugly into the mouth of the combustion tube in preparation for the next test. For proper reproducibility of the results, it has been found necessary to machine the stopper out of either Nylon or Teflon, to adjust the weight of the guide to allow a vigorous return and seating of the stopper after an explosion without jamming and to machine the stopper so that it will, at one and the same time, seat solidly but along a

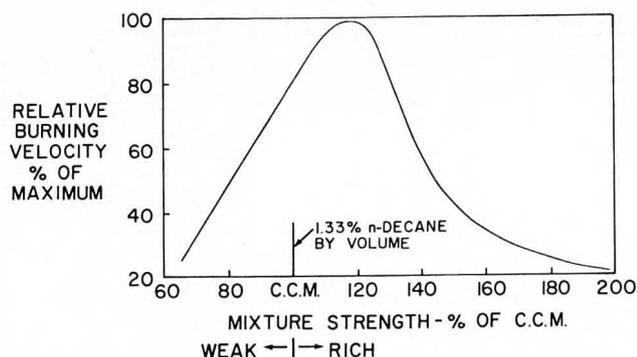


FIGURE 3. Relative Burning Velocities of n-Decane—Air Mixtures.

relatively narrow portion of its circumference. If appropriately set up, such a device exhibits a maximum popping effect during an explosion and permits unattended operation of the unit for a very long time. The noise associated with the propagation of a flame and/or explosion is a third way in which the event can be monitored.

A number of safety features have been incorporated into this design. A relatively high boiling liquid (n-decane boils at 174°C) is generally selected as the test fluid, although the device is amenable to the study of lower boiling materials with suitable modification. With this in view, the normal vapour composition within the confines of the large box containing the units is always well below the lower limit of inflammability of the fuel. However, to doubly ensure this, a fan has been incorporated into the box to expel any vapours to the outside. Observations of the explosion effects are made through a safety glass front and only the push buttons for air and spark are exposed for operation of the units. There is no combination of operating parameters yet found which will result in anything more vigorous happening than has been designed into the apparatus. Operation of an all-glass prototype of this apparatus by students over the past three years under much less carefully controlled conditions has proceeded without

the slightest mishap. Even if the stopper does jam into the mouth of the combustion tube, and an explosion is generated, it has been found that blow-back of liquid occurs into the drying agent in the air inlet tube and the explosive force is thereby released without shattering the container.

DISCUSSION

AS WILL BE OBSERVED, three of the combustion tubes and associated apparatus have been incorporated into the demonstration unit to satisfy the educational criterion mentioned above. Table 1, as posted on the unit, gives the generally accepted limits of inflammability for the test fluid, n-decane, in terms of both vapour-air compositions and the corresponding fluid temperatures which would yield such mixtures. Combustion tubes 1 and 3, which are respectively to the left and right of the central apparatus in the unit, are thermostatted at temperatures which will generate respectively a mixture just above the lower explosive limit and a mixture just below the upper explosive limit. The central unit is thermostatted at a temperature corresponding to a mixture near that which would propagate flame at maximum velocity.

The general form of the relationship between mixture composition, within the explosive limits, and flame velocity is shown on the graph in Figure 3, also as posted on the unit. The observations of the explosion intensity in each of the tubes may be compared to this graph, to yield a preliminary explanation of the effects in terms of differences in flame velocities. An in-depth review of the more

TABLE 1
COMBUSTION
TEST FLUID
NORMAL DECANE

EXPLOSIVE LIMIT	VOL. % IN AIR	CORRESPONDING TEMPERATURE—°C
LOWER	0.85	48
UPPER	5.44	87

rigorous precepts involved in this phenomenon is beyond the scope of this paper. However, an extensive treatment is available in the text by Lewis and von Elbe [2].

It is interesting when demonstrating this unit, to ask students to predict the effect of the grad-

ually increasing test temperature, especially after they have made the observations of the explosion intensity in the first two combustion tubes and before they have observed the effect in the third apparatus. The mildness of the "explosion" in the third tube (at the highest temperature) generally surprises people after they have seen the effects in the other tubes.

It would be desirable to demonstrate, as well, the inability of flame to propagate through the gaseous mixture at compositions just below the lower limit and just above the upper limit. Unfortunately, this would be incompatible with the achievement of the other criteria for this demonstration unit without increasing the number of combustion units to be maintained at different constant temperatures or without increasing the complexity of the operating instructions.

In an arrangement for a laboratory experiment, only one combustion tube and its associated hardware would be required to demonstrate the principles already mentioned as well as several others. Thus, a step-wise increase in temperature and, hence, mixture strength can be achieved by simply altering the thermostat settings appropriately. The whole range of desired mixture strengths could thus be scanned beginning below the lower limit and extending beyond the upper limit. Observations concerning the character of the inflammation and the explosive violence could then be made throughout. In addition, a variety of inflammable liquids could be examined. For example, in our combustion laboratory, the explosive limits for a number of Jet A1 fuels have been examined in such an apparatus. It is interesting to note that the lower explosive limit for such fuels is very close to that of n-decane. For present purposes, however, it is preferable to operate with a fuel of which the composition would be invariant over the long period of use.

Another example of a more exotic application of such an apparatus is in the determination of the lower limit of inflammability of a 40% by volume ethanol-water mixture (as in several alcoholic beverages). The degree to which the vapour pressure of alcohol in contact with such a solution exceeds the value calculable on an ideal solution basis, using Raoult's Law, can in fact, be estimated from such a measurement if the vapour pressure-temperature relationship and the lower explosive limit for pure ethanol is known. The extension of the project to achieve this goal is outlined in Table 2. □

TABLE 2

Extension of Project No. 4—Combustion
Lower Limit of Inflammability of an Ethanol-Water Solution

Data: Ethanol (C_2H_5OH - M.W = 46.08)
Density of pure ethanol = 0.789 g/ml at 20°C
Density of 40% v/v ethanol-water solution = 0.952 g/ml at 15.56°C

(% ethanol (W/W) = 33.1%)

$$\log^{10} P^{\circ}_{C_2H_5OH} = \left(\frac{-0.2185 \times 9673.9}{K} \right) + 8.827392$$

where K = temperature in °K

$P^{\circ}_{C_2H_5OH}$ = vapour pressure of C_2H_5OH in mm Hg.

Assume barometric pressure = 760 mm Hg (unless measured)

1. Determine, experimentally, the temperature at which a 40% v/v solution of ethanol in water reaches the lower limit of inflammability of ethanol vapour in air (determined in tests with pure ethanol to be 4.3 % v/v).
 2. Assuming ideal solution behaviour and attainment of equilibrium, calculate the concentration of ethanol in air corresponding to the experimentally determined temperature.
 3. Using the vapour pressure-temperature relationship for ethanol (see data from Handbook of Chemistry and Physics) and again assuming ideal solution behaviour and attainment of equilibrium, calculate the theoretical temperature at which a 40% v/v ethanol-water solution would produce an ethanol vapour-air mixture at the lower limit of inflammability (4.3% v/v).
 4. Compare the results of 2 and 3 with 1 and explain the discrepancies. Calculate the factor by which the calculated partial pressure in 2 should be multiplied to give the lower limit mixture at the experimentally determined temperature.
 5. Would you expect an alcoholic beverage containing 40% v/v ethanol as well as certain flavour components and sugar to produce vapour at the lower limit of inflammability at a higher or lower temperature than
 - (a) the theoretical temperature calculated in 3?
 - (b) the experimental temperature determined in 1?
- Justify your answers.

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ACKNOWLEDGMENT

The demonstration unit described here was constructed in the machine, electrical and glassblowing shops of the Department of Chemical Engineering at the University of Toronto. The author is extremely grateful and thankful to Messrs. John Aslin and Gord Kearns (machine shop), Ken Adams, K. Atia, K. Kim (Electrical shop) and Fred Leslie (glassblowing shop) for their invaluable assistance in bringing this project to fruition.

M.I.T.'S POLYMER PROGRAM

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WHILE THERE IS substantial interest in polymers in academic circles today, it is a matter of history that early major breakthroughs in polymer chemistry came from the industrial laboratory. Most noteworthy is the classical work of Carothers (1) at DuPont in the late 20's and early 30's which put Staudinger's earlier macromolecular hypothesis (2) on firm footing. Carothers' work opened the way for the rapid development of the polymer industry, but academic

A noteworthy strong point of the polymer course selection is the Polymer Science Laboratory. This course has developed out of the recognition that, for polymers in particular, there is no substitute for first-hand experience.

chemistry departments did not immediately respond to the challenge offered by the new technology. The polymer industry thus found it necessary for many years to provide "on the job" training for its personnel in specific aspects of polymer chemistry. Recent pressures (3) on academic institutions to increase their emphasis on polymer chemistry have received more than casual attention due to the long awaited award of the Nobel Prize for Chemistry to Professor Paul J. Flory, whose own distinguished career began in an industrial environment (4).

The MIT Chemical Engineering Department was one of the early academic institutions to grasp the wide ranging importance of polymer chemistry. In fact, as the MIT Department of ChE evolved out of the Chemistry Department, a significant part of its early research was in the area of what would now be called polymer processing. Professor Warren K. Lewis, around 1920,

was working with his student Charles Almy on the plasticization of cellulose by zinc chloride to make a remarkably tough durable product commonly called "vulcanized fiber", and Lewis also was involved in extensive research on the processing of leather, a classic example of chemical conversion of natural polymers. The general spirit of his work, and the insight of Lewis and his colleagues, are well represented by the book, *Industrial Chemistry of Amorphous and Colloidal Materials*, Warren K. Lewis, Geoffrey Broughton & Lombard Squires (MacMillan, 1942). Professor Edwin R. Gilliland, one time head of the Department, co-directed the synthetic rubber program of the United States during World War II, a program that called for the establishment of emulsion polymerization of styrene-butadiene on a vast scale. Other members of the ChE Department such as Herman P. Meissner, Lamott-duPont Professor Emeritus of ChE, carried out early work on adhesion of polymers and properties of thin films of polymeric substances.

Since approximately 1935 a course on polymers or polymer technology has been among the list of offering of the graduate program. In the late 1950s and early 1960s the polymer program took another major step forward when the teaching was reorganized so as to give three independent subjects: Physical Chemistry of Polymers, Synthesis of Polymers and Structure-Properties Relationships. These have evolved into the present core courses offered today.

Thus the program outlined in the following paragraphs reflects long standing activity in polymers in the MIT ChE Department and a continuing firm commitment to the subject of polymer chemistry in the future. This commitment arises from a conviction that ChE graduates will continue to contribute strongly in the polymer industry.

COURSE AND DEGREE OFFERINGS

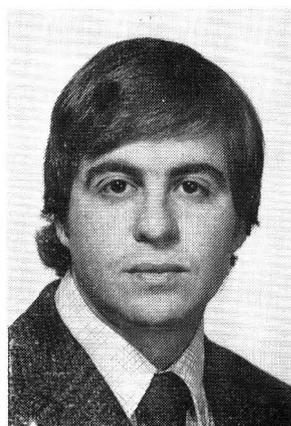
STUDENTS CAN FIND a wide range of polymer-related subjects in the MIT ChE cur-

riculum (see Table 1). Courses are offered over the full range of academic levels, from the freshman course in Polymer Chemistry to advanced graduate seminars or such special topic courses as Polymer Viscoelasticity, Anionic Polymerization Techniques, etc. Those courses marked with an asterisk are offered in parallel each fall semester and constitute the core structure of a highly intensive M.S. program in polymer chemistry which is discussed separately below. Other courses marked with a dagger are integral parts of the undergraduate or graduate ChE curriculum and are offered on a regular yearly basis. The remaining courses are offered routinely on a semiannual basis or more often if there is sufficient student demand.

A noteworthy strong point of the polymer course selection is Polymer Science Laboratory. This course has developed out of the recognition that, for polymers in particular, there is no substitute for first-hand experience in the laboratory even though a large array of lecture courses may

TABLE 1. Polymer Course Selection

COURSE TITLE	TYPICAL TEXT
Intro. to Polymer Chem.	Williams, "Polymer Science"
Structure and Prop. of Matter	DeBenedetto "Structure and Prop. of Materials"
Macromol. Hydrodynamics	NOTES
Surface and Colloid Chem.	NOTES
Structure and Prop. of Polym.	Meares, "Polymers, Structure and Bulk Properties"
Viscoelasticity of Polym.	Ferry, "Viscoelastic Prop. of Polymers"
Polym. Science Lab.	Colins, Bares, Billmeyer, "Experiments in Polymer Science"
Phys. Chem. of Polymers	Flory, "Princip. of Polymer Chemistry
Special Topics in Polym.	Flory, "Stat. Mech. of Chain Molecules
Principles of Polym. Synthesis	Flory, "Princip. of Polymer Chemistry"
Advanced Topics in Polym. Synthesis	NOTES
Network Formation in Polym.	NOTES
Compounding and Processing of Polym.	NOTES
Seminar in Polym. Chem.	—
BS Thesis	—
MS Thesis	—
PhD Thesis	—



Robert E. Cohen joined the faculty in 1973, after completing a year's residence at Oxford University's Department of Engineering Science as an ICI Research Fellow. He is currently a recipient of a DuPont Young Faculty Award and is using the grant to further his research interests in the area of elastomer structure-property relationships. His teaching interests have focused on the development and implementation of laboratory instruction in the polymer area as well as lecturing on the various aspects of polymer properties. (left)

Edward W. Merrill is involved in numerous areas of polymer teaching and research since 1948. His polymer research has resulted in more than 100 publications and has evolved from early work on the rheology of synthetic polymers to increasing efforts in the area of blood and biorheology, and currently concentrates on the subject of bio-compatible polymers. The continuing evolution of the ChE polymer program has been a large part of his teaching focus and the present organization of the graduate curriculum reflects his efforts. He is currently the holder of the Carbon Dubbs Professorship. (right)

be available to stress underlying theory. The laboratory acquaints students with a selection of techniques employed in the synthesis and characterization of polymeric materials. The experiments have been chosen for their practical importance and instructional value. Continuing emphasis is placed on the long-chain nature of the polymer molecule and the influence of this molecular feature on experimental procedures and results. A selection of experiments for the polymer lab is shown on Table 2 and are described adequately in the required text (Collins, Bares and Billmeyer, *Experiments in Polymer Science*, Wiley, 1973). Extensive notes have been prepared to describe those experiments which do not appear in the text. Several of the standard commercial instruments used in the lab are indicated in Table 2. Exposure to such widely used devices is an important aspect of the course content.

Any of the courses listed in Table 1 may be taken, with proper prerequisites, as technical electives by students who are pursuing a Bachelors

or Masters Degree in ChE. Such students often elect to fulfill their BS or MS thesis requirements by conducting a research project under the direction of one of the ChE faculty with polymer research interests. Upon successful completion of the thesis the student then receives a BS or MS degree with specification in ChE. A separate route to a polymer intensive Masters degree without specification in ChE is described below. The PhD or ScD degree requires no formal participation in polymer course work. However, graduate students who intend to pursue a doctoral degree in a polymer related area are strongly encouraged to select courses which will assist in their research effort and also to broaden their view of the polymer field.

TABLE 2. Polymer Science Laboratory

POLYMER SYNTHESIS

- *1. Free radical polymerization of lauryl methacrylate, following the kinetics by direct weighing techniques.
- 2. Condensation polymerization of ω -aminoundecanoic acid, following the kinetics by end group analysis and by bulk viscosity measurements.
- 3. Interfacial polymerization of nylon 6,6.

POLYMER CHARACTERIZATION

- *1. Light scattering determination of molecular weight; *Sofica Whippler Photometer*.
- *2. Dilute solution (intrinsic viscosity) determination of molecular weight.
- *3. Gel Permeation Chromatography determination of molecular weight and molecular weight distribution; *Waters, Inc. Model 200 GPC*.
- *4. Equilibrium swelling of cross-linked networks.
- *5. Nuclear magnetic resonance determination of copolymer composition (in cooperation with Chemistry Department). *Hitachi-Perkin Elmer R-20B*.
- 6. Wide angle X-ray scattering—morphology of crystalline polymers.
- *7. Differential scanning calorimetry-analysis of melting points and glass transition temperatures. *Perkin-Elmer DSC 1B*.
- 8. Differential Thermal Analysis, *DuPont DTA and TMA Model 900*.
- 9. Transmission Electron Microscopy—*Phillips EM200*.

POLYMER PROPERTIES

- *1. Tensile stress-strain and stress relaxation, *Instron Tensile Tester*.
 - 2. Dynamic Mechanical Properties—*Rheovibron DDV-II-C*.
 - 3. Tensile and shear creep and recovery.
 - 4. Gas diffusion through polymers.
- *Required experiments, others are optional.

MASTERS DEGREE

THIS PART OF THE overall polymer program is especially suited for students who as undergraduates have had a strong training in chemistry. Such training may form part of the requirements for a BS degree in ChE and in certain other disciplines. The degree of BA or BS in Chemistry would virtually insure an appropriate background. In any case, physical chemistry including thermodynamics and a first course in organic chemistry should be part of the background. Women graduating with any of the above degrees, including those with no engineering background, such as chemistry majors in liberal arts colleges, are encouraged to consider applying for admission to the program.

Beginning in the fall term, the first half of the program provides intensive and coordinated instruction leading to a comprehensive view of polymers, showing how the areas of specialization relate to one another—for example, how macroscopic properties are influenced by molecular “microstructure” which in turn is influenced by method of synthesis. Parallel with the basic subjects of instruction the students have extensive laboratory work in the principal techniques for synthesis, analysis, and testing of polymers. During the fall term the student participates in a weekly seminar. Several of these (see Table 3) are devoted to discussions by visitors from industry and other universities; other meetings are devoted to joint discussions led by the regular teaching staff. Through the seminar the student gains an additional perspective on polymers that will assist him in selecting a topic for the research that forms his MS thesis.

In the month of January, ordinarily a period of Independent Activities at MIT, the student can devote a major part of the time to the MS thesis, preparing the literature review, acquiring the apparatus and instrumentation appropriate to the task, and beginning his work, which continues through the Spring Term. The three summer months are entirely open for research effort on the MS thesis, thus virtually assuring completion of the degree in one calendar year.

A principal objective of the undesignated MS program is to prepare students to take up an immediate professional career involving polymers in a variety of industrial areas, including chemical, textile, food, mechanical, electrical, pharmaceutical and aeronautical/space industries. Pres-

ent indications are that the student who has received the MS following this program will find a wide and ever increasing range of offers of employment, at levels of starting salary significantly above that for the graduate with the BS degree.

Alternatively, a student in the program has the option of preparing for advanced study on polymers leading to a doctorate in ChE. The student who decides to continue an advanced program of study beyond the MS degree can modify the program to include one or more subjects drawn from the core courses of the ChE department in order to prepare for the doctoral qualifying examinations.

POLYMER RESEARCH

The MIT ChE faculty carry on a vigorous and wide ranging research program in numerous areas of polymer science. There are adequate ongoing research projects, both experimental and theoretical in nature, to suit the tastes and interests of nearly anyone interested in conducting a thesis project in the polymer area. The considerable facilities and specialized equipment for polymer research are readily available to students within the ChE department and there are numerous avenues available for cooperation within the MIT community.

At present the ChE Department, owing to a lack of adequate space, must conduct many of its research projects, polymers included, in a number of widely separated laboratories around the MIT campus. However, in January of 1976, the department will move into its new building the construction of which is now nearly complete. Nearly two thousand square feet of laboratory space have been set aside for polymer research and considerable new research apparatus are being acquired. This unification and improvement of the physical facilities will serve to strengthen the existing research effort in the polymer area, and will allow for an expanded polymer research program in the future.

A special aspect of the program is liaison with the Center for Macromolecular Research (CMR) in Strasbourg, which is affiliated with but operates independently from the University of Strasbourg under the Centre National de la Recherche Scientifique of France. Visiting Professor Paul Rempp is a director of research at this center and has had a long history of association with MIT dating back to his post-doctoral

TABLE 3. Visiting Seminar Speakers (Fall 1974)

SPEAKER & AFFILIATION	TOPIC
Dr. R. J. Roe, Bell Telephone Labs	Interfaces in Polymers
Prof. R. Stein, University of Massachusetts	X-Ray and Light Scattering Studies of Multiphase Polymers
Dr. D. J. Meier, Midland Macromolecular Institute	Block Copolymers
Prof. W. R. Krigbaum, Duke University	Polymer Interfaces
Dr. T. Alfrey, Dow Chemical Co.	Mechanical Properties of Polymers

fellowship with Walter Stockmayer in 1958. It is planned to develop a continuing collaboration with the Strasbourg group involving the exchange of graduate students and post-doctoral fellows.

In the spring 1975 term, Dr. Rempp will offer the subject Advanced Polymerization Processes and will participate in the instruction of Network Formation in Polymers. Dr. Philip Gramain, renowned for his work combining synthesis of polymers and physical characterizations will be Visiting Research Associate in the Department. Professor Henri Benoit, General Director of the CMR, will be in residence for three weeks in the spring of 1975 as speaker in the Polymer Seminar.

SUMMARY

IN THE ABOVE paragraphs we have outlined the polymer teaching and research program in MIT's ChE department. The program is, and we believe will continue to be, a valuable component of the overall ChE curriculum. The department's long standing interest in polymers has evolved into the present coordinated effort which provides diversity and flexibility in subject and degree offerings. This program will continue to evolve to keep abreast of the changing aims and goals of education in the polymer field and will continue to be responsive to the ever increasing needs of the polymer-related industry. □

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CHEMICAL ENGINEERING EDUCATION AND RESEARCH IN POLAND

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The present paper relates the activities of a visit made by the author under the auspices of the U.S. National Academy of Science to Poland. Essentially, a detailed description of chemical engineering education and research in Poland is given. In addition, a thorough analysis is made of these activities so that conclusions are reached with regard to quality, problems and future directions.

WARSAW I

UPON ARRIVAL IN Warsaw I met Drs. Zahorski and Ziabicki from The Institute for Basic Problems of Technology (IBPT). My general impression of the group in the Laboratory for Polymer Physics (headed by Dr. Zahorski) was that they were well qualified and involved in first rate research. They suffered, however, from a serious lack of laboratory equipment. Because of this, most of their research was theoretical. There were a large number of doctoral candidates working for both Drs. Ziabicki and Zahorski (about twenty or so). The background of these students was varied—some were physicists, some chemists, engineers and even biochemists. There appeared to be less restriction in changing graduate fields than in the United States. In fact, the boundary between engineering and scientific disciplines was much more fluid than in our country.

I was surprised to find that all doctoral candidates were handled within the Polish Academy of Science without involving a university. While some scientists are jointly appointed to PAN and a university, this is not very common; and consequently, the academy grants its own doctorates.

Next I spent some time with the Laboratory for Fluid Mechanics, also a part of IBPT. My contacts here were Drs. Herczynski and Szaniawski. This group had somewhat more extensive experimental facilities. The research program in the Fluid Mechanics Laboratory seemed to be directed toward esoteric problems. They were, for example, interested in shock tubes. There didn't seem to be any push toward industrial or applied problems. Generally, the Fluid Mechanics Laboratory seemed



Figure 1. The statue of Copernicus between the Polish Academy of Science and Warsaw University.

to be more isolated than the Polymer Physics Laboratory. Perhaps part of the problem was that the scientists in the latter group had been either in Polish industrial laboratories or overseas, while the Fluid Mechanics Group had essentially only their PAN background.

I also continued to discuss research topics with the Polymer Physics group. The principal efforts were being directed to polymer-solvent systems, viscoelasticity and statistical thermodynamics of polymers.

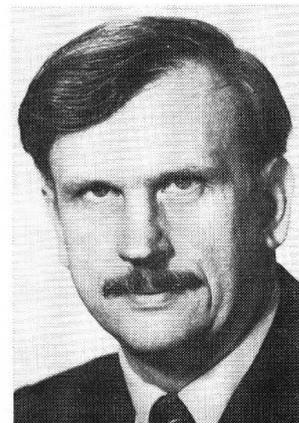
ON TO CRACOW

MY NEXT STOP was Cracow. I visited the Technical University and specifically Dr. M. Mrowiec, the Head of the Institute for Chemical Engineering, and an Associate Dean of the University.

In discussing Polish technical higher education, it became apparent that great emphasis was being placed on the training of engineers and applied scientists. There were no employment problems since the government provided jobs for all such graduates.

The Polish system is based on a five-year program which leads to the degree of Magister (i.e., Master's degree). The curriculum provides for either an industrial practicum or a university based project in the fifth year. In the applied chemistry and chemical engineering areas the course of study is essentially the same for the first two years. Then, during the third and fourth years the chemical engineering and applied chemistry programs diverge. The general impression that is given is that the chemical engineering degree is more rigorous and demanding. Course content appears to be more practically oriented than in American programs. There is, however, a strong emphasis placed on the basic sciences.

The faculty at Cracow were dedicated and appeared to be well qualified. Practically all of them were educated entirely in Poland. The principal exception was Dr. Mrowiec, who had received German graduate training. Students seemed to be bright and hard working. In Poland they are a somewhat privileged class since they receive free education, and special benefits such as trolley and bus passes and various discounts. An impressive feature was that the Cracow Technical University, although a fairly new institution, had several thousand students. In fact, it would have been larger than nearly all U.S. Colleges of Engineering.



Richard G. Griskey received his B.S. in Chemical Engineering from Carnegie-Mellon University in 1951. From 1951 to 1953 he was a First Lieutenant in the Combat Engineers of the U. S. Army Corps of Engineers. In 1953 he entered Carnegie-Mellon where he was awarded an M.S. (1955) and Ph.D. (1958).

The National Academy of Science appointed him as Senior Visiting Scientist to Poland in 1971. In the same year he was appointed Dean of the College of Engineering and Applied Science of the University of Wisconsin-Milwaukee as well as Professor of Energetics.

He has had industrial and consulting experience with DuPont, Celanese Fibers, Celanese Research, Phillips Petroleum, Thermo Tech Inc., Hewlett-Packard, Litton Industries and the U. S. Veterans Administration. He is a member of AIChE, Cryogenic Society, Society of Plastics Engineers, ASEE, and the Society of Rheology.

Dr. Mrowiec went into quite a bit of detail in describing Chemical Engineering education in Poland. He indicated that there were five other Institutes of Chemical Engineering located in the Technical Universities of Warsaw, Lodz, Gliwice, Wroclaw and Szczecin. The relative size of these Institutes and their heads are shown in Table II.

Generally the Institutes at Warsaw and Lodz are felt to be the best in Poland. It should be noted that Professors Ciborowski and Hobler are both members of the Polish Academy of Science, a prestigious recognition in Poland. Hobler is the "grand old man" of Polish Chemical Engineering, and although in his seventies, is still active.

One point of interest was that the Technical Universities all gave five year Master's programs as a first degree, despite considerable sentiment to return to the four year baccalaureate program as a first degree. The Technical Universities also had doctorate programs, although the effort in this area at Cracow was just beginning.

Dr. Mrowiec also mentioned that there was a rough Polish equivalent to the Bachelor of Technology degree now so much in vogue in the United States. The Polish program took four years and was apparently designed to produce personnel for

factory or field operations. None of the Technical Universities offered this program. Instead, institutions, apparently several steps below the Technical Universities, in locations such as Bialystok offer this curriculum.

NEXT STOP—LODZ

I LEFT CRACOW for the Institute of Polymers of the Lodz Technical University, where I met with Professor Dr. Marian Kryszewski. His operation at Lodz was quite interesting since he simultaneously was affiliated with Lodz Technical University and the Polish Academy of Science. Dr. Kryszewski's laboratories were very impressive. His equipment was highly sophisticated and the purchased items were of the best quality. In addition, he had modified many devices and in some cases fabricated novel experimental units. In many ways his experimental facilities were the best that I saw in Poland.

I spent two days at the Institute for Man-Made Fibers. This unit was a directly supervised facility of one of the ministries of the Polish government. In essence then, it was neither a university nor a unit of the Polish Academy of Science, but rather, a government laboratory. As such, the emphasis was heavily on applied areas. The laboratories were extremely well equipped with Japanese, West German, U.S., and English instruments. For example, they had a Hitachi electron microscope and a Siemens X-ray unit. The quality of the laboratory personnel was high.

The Polish system is based on a five-year program which leads to the degree of Magister (i.e., Master's degree). The curriculum provides for either an industrial practicum or a university based project in the fifth year.

In fact, the scientists and engineers in the Institute would compare favorably with the best in the industrial laboratories of the United States.

One problem which seemed to retard their activities was a lack of direction from the government. There did not seem to be a clear notion of what fibers should be emphasized. Some of the research, while interesting, did not give data that would help those in the industrial area.

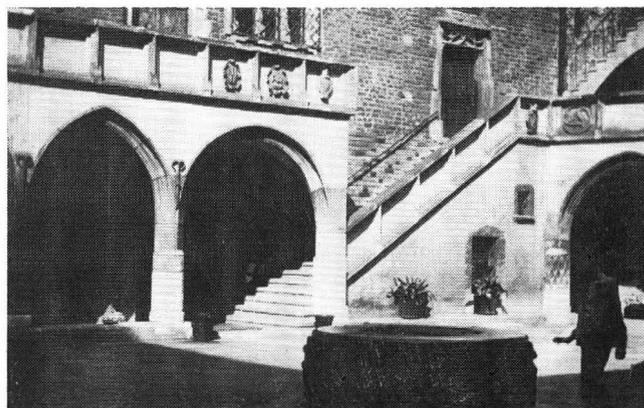


Figure 2. One of the oldest universities in the world, Jagiellonian University in Cracow, was founded in 1364.

RETURN TO WARSAW

FOR MY FINAL week I visited two institutions—the Institute of Chemical Engineering of Warsaw Technical University and the Institute for Industrial Chemistry (a government laboratory similar to the Institute for Man-Made Fibers in Lodz).

My host at Warsaw Technical University was Dr. Ciborowski, a member of the Polish Academy of Sciences, and one of the most prominent engineers in Poland. He has traveled widely and had just returned from Cuba prior to my visit. Dr. Ciborowski studied at M.I.T. just after World War II under the auspices of UNRRA. Because of this he had an excellent grasp of our system of technical higher education.

His Institute was most impressive. Unlike Cracow where there were space and equipment problems, his facilities were spacious and fairly well equipped. Much of his laboratory facilities were fabricated in one of the best machine shops I saw while in Poland. Dr. Ciborowski's sophistication also showed up in his curriculum and faculty.

The graduate program at Warsaw was most impressive. There was a real effort to build up sophisticated projects in such areas as chemical reactor design, scale-up and optimization techniques, and other areas of practical significance requiring thorough fundamental treatment.

I should mention two members of Dr. Ciborowski's faculty of note. One, Dr. Marcinkowski who was working on his Dr.(Hab) in the area of scale-up of chemical reactors. The sophistication and innovation displayed were impressive. The other, Dr. Selecki is a first-rate inorganic chemical engineer who has a wide variety of unusual inter-

ests relating to the application of inorganic chemistry.

Dr. Ciborowski himself should not be neglected. He has continued to carry out impressive research in the areas of heat transfer and fluidized bed behavior. As a general impression I would rank both the Institute of Chemical Engineering at Warsaw and Dr. Ciborowski most highly.

My final Warsaw visitation was made to the Institute of Industrial Chemistry. Dr. A. Plochocki, whom I had corresponded with over a number of years, was my host.

This Institute, a government laboratory, was most impressive in facilities and equipment areas. They had both excellent chemical engineering and plastics processing laboratories. In addition, they seemed to have a sense of direction. Much of their work was research that would directly benefit the Polish economy.

Dr. A. Cybulski was doing very fine work on chemical reactor systems, the utilization of which would benefit the Polish economy. Dr. Plochocki was doing the same kind of first class effort in the area of Plastics Processing. There was a real effort to bring about greater understanding so that the Polish plastics industry could grow in a meaningful way.

SUMMARY AND CONCLUSIONS

MY TRIP TO POLAND gave me an opportunity to survey the various types of laboratories in that country, the status of technical higher education and the general quality of research in the area of polymers.

There are three principal types of laboratories in Poland. The first are those under the jurisdiction of the government (such as the Institute of Man-Made Fibers in Lodz and the Institute for Applied Chemistry in Warsaw). These laboratories are well equipped and even have sizeable amounts of new and sophisticated units from hard currency areas such as the United States, Japan, West Germany, France and England. Their staffs are high caliber and have good esprit de corps.

The next category was the laboratories of the Polish Academy of Science. These units had probably the best technical people in the country. There was good rapport with the universities or with potential graduates through their own doctorate programs. Generally, however, the facilities were poor. The little equipment available came mainly from Russia, Czechoslovakia or East Germany.

Finally there were the laboratories in the universities which were probably the poorest in terms of facilities and equipment. There was a dangerous separation in some cases from the "real" world which has proven disastrous to graduate students in this country. Faculty were, however, of high caliber and were able to do excellent work when in contact with outside laboratories. There seems to be strong sentiment to make a four-year program the first degree. Interestingly, this is the opposite of current trends in U.S. engineering education.

A typical ChE curriculum resembles a strong traditional U.S. chemical engineering curriculum of about fifteen years ago. Such courses as chemical technology, machinery, and unit operations no longer in vogue in the U.S. are still part of the Polish curriculum. In spite of this, the program appears to be sound and perhaps better to be sound and perhaps better suited to Poland's needs than our courses of study.

Students in Poland are a privileged class since they receive free education, and special benefits such as trolley and bus passes and various discounts.

The curricula in polymers are essentially polymer chemistry with some physics intertwined. There is absolutely nothing that resembles the interdisciplinary U.S. programs which include engineering, chemistry, physics and materials science. A strong curriculum emphasizing polymer engineering is badly needed in Poland. Especially so if the polymer industries there are to progress.

One impressive feature of Polish technical higher education was the large number of female students. In some curricula they constituted a majority. There were large numbers who were not only doctorate candidates, but also active researchers. Perhaps the example of Marie Curie and a different societal viewpoint accounts for this.

I was very much impressed with the quality of the research being carried out in Poland. Despite equipment and facility limitations, the Polish engineers and scientists performed consistently at a high level. Particularly impressive were Drs. Ziabicki, Zahorski, Kryszewski, Cybulski, Plochocki, Selecki, and Ciborowski. It is my personal feeling that more scientific interchange would be beneficial to both nations. □

THE CHEMI PROJECT

Continued from page 17.

ate a student's achievement of those objectives." EMMSE (Educational Modules for Materials Science and Engineering) held a one day meeting to arrive at some consensus concerning the description of a module. The most important agreement reached at the meeting was that each module should be explicitly described in several dimensions, with the length as the principle parameter. The following table shows cross-referencing to other terminologies which describe length.

COURSE DESCRIPTION	MODULE DESCRIPTOR (approximate time)	BOOK ANALOG
single aspect	5-min module	paragraph
single topic	15-min module	section
1 classroom lecture	1-hour module	'n' sections
1 week's lectures	2-hour module	chapter
1 semester's lectures or 1 course	45-hour module	book

The descriptors for a given module might be as follows:

- Four modules on "Thermodynamics"
- Discipline/Level: Engineering/college juniors
- Length: 15 minutes each
- Medium: 16 mm color-sound technicolor movie cassette

For the CHEMI Project all the modules will be text (print) modules on 8 1/2 x 11 paper. Each module will be roughly from 7 to 15 pages in length (excluding problem solutions), single spaced, with an educational content equivalent to about a one hour lecture, and covering, in general, a single concept.

The entire ChE community is invited to join in this venture by writing modules in their areas of interest. The following recognition and compensation will be given to module authors.

- Wide distribution of modules to the ChE community with identification of author and institution in the copy and on the cover
- Announcement of the availability of modules in the CACHE NEWSLETTER and in periodic news releases to ChE journals.
- \$50.00 Honorarium for each module.
- The review process is designed to enhance the professional recognition of the author's work and make it comparable to that of research articles.

While many modules have already been commissioned, many have not. If you are interested in writing a module, please contact the appropriate editor listed below. He will then send you a complete listing of module topics and an author's kit including a sample module.

The project is directed by Ernest Henley (U. of Houston) and his assistant director is William Heenan (U. of Puerto Rico). The editors in charge of the 7 curriculum areas are: Kinetics—Billy Crynes (Oklahoma State U.) and Scott Fogler (U. of Michigan), Thermodynamics—Bernie Goodwin (Northeastern U.) Control—Tom Edgar (U. of Texas), Transport—Ron Gordon (U. of Florida),

Stagewise Processes—Ernest Henley (U. of Houston), Design—Bob Jelinek (State U. of New York, Syracuse) and Bob Weaver (Tulane U.), Stoichiometry—Dave Himmelblau (U. of Texas).

The entire project is under the oversight of a steering committee: Lawrence Evans (M.I.T.), Gary Powers (Carnegie-Mellon U.), Ernest Henley (U. of Houston), David Himmelblau (U. of Texas), Duncan Mellichamp (U. of California), and Robert Weaver (Tulane U.). □

William A. Heenan and
Ernest J. Henley
University of Houston

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Editor's Note:

At a talk given at the University of Florida, Prof. John J. McKetta of the U. of Texas read the following note he received from a student. The editor thought we would share this with our readers.

The Last Psalm

*Dr. McKetta is my Professor, I shall not pass.
He maketh me to exhibit my ignorance
on every quiz,
He telleth me more than I can write down,
He lowereth my grades.
Yea, though I walk through the corridors of the
classrooms of knowledge,
I cannot learn.
He tries to teach me,
He writeth the equations before me in hopes
that I can understand them,
He bombardeth my head with "rules of thumb".
My sliderule freezeth up.
Surely enthalpies and entropies shall follow me
all the rest of my life,
and I shall dwell in the College of
ChemEngineering forever.
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