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A LETTER TO CHEMICAL ENGINEERING SENIORS

Should you go to graduate school?

Through this special issue on graduate education, Chemical Engineering Education invites you to consider graduate school as an opportunity to further your professional development. We believe that you will find that graduate work is an exciting and intellectually satisfying experience that greatly enhances your ability to obtain responsible and challenging positions in industry and teaching. We also feel that graduate study can provide you with insurance against the increasing danger of technical obsolescence. Furthermore, we believe that graduate research work under the guidance of an inspiring and interested faculty member will be important in your growth toward confidence, independence, and maturity.

What is taught in graduate school?

In order to familiarize you with the content of some of the areas of graduate chemical engineering we are including in this issue articles describing graduate courses that have been taught by professors who have specialized in these fields. In doing so we wish to make clear the following: 1) that there is some variation in the content of individual graduate courses in the same area as taught at various schools (e.g., many schools teach transport phenomena sequences, while others teach individual courses in fluid mechanics, heat transfer, and mass transfer), 2) that we have not included all of the areas in which graduate courses are taught (e.g., we have not included a design course, per se), and 3) that the professors who have written articles for us are by no means the only authorities in those fields, nor are their departments the only departments which emphasize that particular area of study.

What is chemical engineering research?

We are dedicating this graduate education issue to an outstanding chemical engineering researcher and teacher: the late Allan P. Colburn. Although Dr. Colburn's career included work in education, industry, and government, he is best known among educators for his pioneering research in many areas of chemical engineering. This research, while based on fundamentals, was directed toward the ultimate attainment of an engineering answer, usually in the form of the many Colburn equations or correlations that are still used by practicing engineers. As an example of someone to emulate in your own graduate career, we urge you to read the article by Professor Olaf Hougen on Allan Colburn's activities as a graduate student. (Incidentally Professor Olaf Hougen was himself featured by CEE (Summer 1968) and is also worthy of emulation).

Where should you go to graduate school?

It is common for a student to broaden himself by doing graduate work at an institution other than the one from which he receives his bachelor's degree. Fortunately there are many very fine chemical engineering departments in the United States, each of which has its own "personality" with special emphases and distinctive strengths. For example, in choosing a graduate school you might first consider which school is most suitable for your own future plans to teach or go into industry. Or if you have a specific research project in mind, you might want to attend a university which emphasizes that area and where a prominent specialist is a member of the faculty. On the other hand if you are unsure of your field of research, you might consider a department that has a large faculty with widely diversified interests so as to ensure for yourself a wide choice of projects. Or you might prefer the atmosphere of a department with a small enrollment of graduate students. In any case, we suggest that you begin by writing the schools that have provided information on their graduate programs in the back of this issue. You will probably also wish to seek advice from members of the faculty at your own school.

But wherever you decide to go, we hope that you make the decision to continue your education in graduate school.

Sincerely,

Ray Nahin
Chemical Engineering Education
University of Florida
Gainesville, Florida 32601

NOTE TO DEPARTMENT CHAIRMEN—Additional copies of this Graduate Education Issue are available at no charge (while supply lasts) to your seniors who are interested in graduate work. Please write the Editor at the above address, stating the number of copies needed.
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Fellow Division Members:

Chemical Engineering Education is completing its second year with its new format. Under the able Editorship of Ray Fahien—assisted by his colleagues Bob Bennett and Mack Tyner—CEE has drawn praise from chemical engineers in industry, teaching and government. We of the Publication Board believe we have a good thing going and feel a strong obligation to continue to seek the necessary financial support.

The financial support for CEE has come chiefly from two sources—industrial concerns and the departments of chemical engineering. A grant from NSF (to the Summer School) helped us during our first year. Our financing method appears sound; we have balanced our budget. Nevertheless, we have to abolish free subscriptions to CEE members. Cost is one reason, another is duplication—most Division members are also faculty members. Furthermore, our present system of sending each department 10 copies regardless of size, has meant that in the large departments some faculty members seldom saw the journal, while some small departments received an over-supply.

Consequently, the Publication Board recommended, and your Executive Committee approved the following plans for CEE distribution:

1. Chemical Engineering Departments will be asked to request a definite number of copies at $4/year for each of the four issues in 1970, with a minimum contribution of $25/year. (They may pay for these through departmental funds or faculty contributions or both.)

2. ASEE-Chemical Engineering Division members may request (on the attached form) individually addressed copies to any address and pay $6/year starting in January 1970.

3. Libraries and other subscribers that are not members of the Chemical Engineering Division of ASEE may subscribe as before at $10/year.

As a matter of interest, we are attempting to make arrangements with ASEE to have our subscription fee collected with the annual dues. This may be in effect in June 1970 for payment of 1971 subscriptions. Again, this applies only to those desiring individual subscriptions.

Jim Weber is Regents' Professor and Chairman of the Department at the University of Nebraska. He has been at Nebraska since 1948 when he received the PhD from the University of Pittsburgh. Jim is the author or co-author of fifty articles and serves as an industrial consultant. Besides ASEE, he is a member of AIChE, ACS, and AAAS, and a registered professional engineer.

We wish to continue to give you a first rate publication and thank you for past support. We hope for your continued support and that you appreciate the need for this change.

Very truly yours,

James H. Weber
Chairman, Publications Board
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from our READERS

Lynn responds to Fredrickson

Sir: Dr. A. G. Fredrickson’s essay “The Dilemma of Innovating Societies” (CEE, Summer 1969) points out a number of the problems facing our society today. The effects of increasing pollution, exploiting wilderness areas, and a rapidly expanding population are steadily making the world a less pleasant place to live. It was therefore a disappointment to see Dr. Fredrickson weaken the strength of his message substantially by overstating it in an emotional tirade against straw villains of his own construction.

It is, for instance, unconvincing to denounce the effects of man’s activities on our environment by proclaiming a higher-than-human set of values. There is no reason to think that nature prefers alligators to algae, condors to crickets, or any of these to mankind. Such preferences are human value judgments and should be defended as such. The holier-than-thou stance only beclouds the issue.

If Dr. Fredrickson really questions the relative happiness of today’s farmer astride his air-polluting tractor I would suggest that he try spending a summer of 12-hour days plowing behind a mule. A good look at Van Gogh’s “The Potato Eaters” might also be instructive. The issue clearly is not one of slowing down technological innovation but rather of directing innovative efforts to the solution of the problems that are now becoming pressing.

It may be that society should have foreseen the urgency of these problems one or two generations ago. However, one should remember that 20-20 hindsight is a common virtue and also that no amount of castigation will change the events of the past. Emotional polemics directed against over-simplified whipping boys are highly favored today by political extremists of the left and the right, super-conservationists, gung-ho developers, and many others with a Cause. The trouble with such tactics is that they alienate those whose support might be won by a rational approach.

If the need to solve the problems arising from the growth of population and technology is real, and I believe that it is, then well reasoned arguments to this effect can surely be found. It is clear that we have or can develop the technology to solve these problems if we can get general agreement within our society that they need to be solved. Attaining such agreement will require persuasive leadership, factual knowledge, and considerable persistence. I submit that very few will be persuaded by being told that they are simpleminded votaries of the Cult of the Product, believers of the Creed of Technology, and preachers of the Gospel of Growth.

Scott Lynn
University of California, Berkeley

Corrections from Lee

Sir: Enclosed please find a corrected copy of the short article entitled Transport Phenomena: Equations of Change, which was printed in the summer, 1969 issue of CEE. Please note that equations 7, 9, 11, 15, 16, 17, 19, 20 are corrected, where originally either a small ~ (for pressure) is missing or is mixed up with p (for density).

V. J. Lee
University of Missouri

Editors Note: CEE regrets that Professor Lee did not correct this error on the galleys he received.

Praise from the Veep

Sir: I certainly appreciate receiving the copy of Chemical Engineering Education and was particularly interested in seeing the articles involving Stu Churchill.

A. L. Conn
Vice-President, AIChE

(Letters Continued on page 207)
ALLAN PHILIP COLBURN**

OLAF A. HOUGEN, Professor Emeritus
University of Wisconsin
Madison, Wisconsin 53706

ALLAN PHILIP COLBURN was my first student in graduate research directed towards a doctorate degree in chemical engineering.

Allan was born in Madison, Wisconsin, on June 8, 1904. His father, Willis P. Colburn*, at that time, after twelve years of high school teaching, was enrolled as a student in philosophy at the University of Wisconsin. Upon graduation in 1905 Willis accepted a position as principal of the high school in Rhinelander, Wisconsin. It was here that Allan spent his childhood and received his elementary and high school education. In June 1922 the Colburn family moved to Wauwatosa, a suburban city adjoining Milwaukee, where Willis was employed as principal of a local high school.

In June 1922 Willis Colburn came with his son Allan to my office to consider enrolling him in the College of Engineering of Marquette University in Milwaukee for a period of two years prior to enrollment in chemical engineering at the University of Wisconsin. [The chemical engineering building was then located on the south shore of Lake Mendota at the foot of Park Street.] From Allan's superior high school record and his unusual intelligence, I readily agreed that this plan had much merit not only in the economy of living at home but also in the cultural advantages associated with a sectarian school of high repute. At Marquette University Allan received undergraduate instruction in general chemistry, mathematics, physics, English, shopwork and surveying. Imagine! Surveying was a required course in many curricula of chemical engineering 44 years ago. On September 12, 1924 Allan enrolled as a Junior at the University of Wisconsin. I served as his adviser in his junior year; and Professor Otto L. Kowalke in his senior year.

The period 1920 to 1930 was critical and transitional in the development of chemical engineering education. The year 1923 marks the beginning of the American system of education in chemical engineering with the publication of the text, “Principles of Chemical Engineering” by William H. Walker, Warren K. Lewis, and William H. McAdams. At Wisconsin the curriculum was at that time predominant in conventional engineering courses with instruction in chemical engineering slowly emerging from descriptive courses in industrial chemistry supplemented by laboratory experiments largely empirical in nature.

*The records of Platteville Normal School (now Wisconsin State University—Platteville) show that Willis Paul Colburn, a resident of Grant County, Wisconsin, attended Platteville Normal School in three school years 1886-87 and 1889-91 receiving a diploma in 1891. After graduation he served as high school principal at Potosi, Cassville and Viroqua, Wisconsin. He married Jennie Grimm of Cassville. In 1903 he attended the University of Wisconsin in Madison as a student in philosophy receiving a bachelor of philosophy degree (BPh) in June 1905. In later life he returned for graduate courses in Education in 1914 and in the summer session of 1929.

**This sketch was prepared for the dedication ceremonies of the Allan Philip Colburn Chemical Engineering Building at the University of Delaware, Sept. 20, 1968.
A humanitarian goal in life was manifest in his selection of liberal elective courses essential for a well rounded citizenship.

Allan set his goal early at the highest professional level not only towards advanced studies and research leading to the doctorate degree but also in seeking a career of high professional and civic responsibility. A humanitarian goal in life was manifest in his selection of liberal elective courses essential for a well-rounded citizenship. In this selection Allan was guided by his father whose own major college studies had been in philosophy and by Professor Kowalke. In liberal courses he was fortunate in choosing five of the most popular and inspirational professors at Wisconsin, namely, William H. Kiehoffer in Economics, Louis Kahlenberg in the History of Chemistry, Max Otto in Philosophy, A. A. Vasiliev in Hellenistic Civilization, and Daniel W. Mead in Contracts and Specifications. Mead's course was essentially one in engineering ethics based upon Mead's world wide experiences in the construction of dams and power plants. Professor Kiehoffer was the campus spark plug of enthusiasm in his animated lectures on conventional principles of economics injecting life into an otherwise dull subject. Professor Max Otto held a similar position in philosophy and logic. The course in Hellenistic civilization described the Golden Age of Greece, the causes of its origin and decline. With a delightful sense of humor Kahlenberg portrayed the joys and frustrations of scientific discovery in the lives of great chemists. These five professors, combined with parental influence and that of Professor Kowalke gave Allan an altruistic outlook on life and in his dedication to highly ethical and benevolent standards. This served him well in his later administrative responsibilities and projects of community welfare.

The present day stress on the importance of liberal courses in training of engineers was met by Colburn 40 years ago. In his college years, Allan became a proponent of the Single Tax theory of economist Henry George. This typified student protest forty years ago in contrast to the violence of today.

The professional staff of the Chemical Engineering Department in 1924 consisted of Professors Otto L. Kowalke, Oliver P. Watts and myself. Courses in industrial chemistry and unit operations were given by Professor Kowalke, applied electrochemistry by Watts and a calculation course, applied thermal chemistry, by myself. Allan was graduated in June 1926 with a bachelors degree in science (BS) and high honors. An Engineering Fellowship was awarded him for continuation in graduate studies and research. This fellowship was later renewed for two additional years. At this time a new dormitory system for men was established at the University of Wisconsin. Allan was one of the first graduate students to be appointed as House Fellow. The responsibilities of this position entailed living with undergraduate students as counsellor, guide and friend.

Allan received his MS degree in 1927 and PhD degree in 1929.

In his graduate years Allan’s two closest friends were Kenneth M. Watson and Louis F. Warrick. The former became a prominent chemical engineer in his contributions to education and industrial practice and the latter became the young State Sanitary Engineer of Wisconsin in 1927. A recent letter from Louis Warrick restores an intimate insight into Allan’s zest for living and some of the extra curricular activities he enjoyed during student days.

Before accepting a position with du Pont, Warrick and Colburn had made enthusiastic plans to form a partnership as consultants in solving problems in the abatement of water pollution and disposal of industrial wastes. Already forty years ago these two young men were aware of the dire consequences of water pollution, the irrevocable evils of which are so strikingly evident today.

The research project assigned to Allan for his doctorate thesis was to obtain experimental data on heat and mass transfer coefficients in the condensation of water vapor from saturated air streams in a tubular gas condenser and to formulate correlations based thereon useful for design and operation. This project differed from conventional dehumidification in that it involved air saturated with water at high temperatures with great reductions in volumetric and mass flow rates of the gas-vapor stream during cooling and condensation.

The Committee on Condensing and Scrubbing of the American Gas Association had collected operating data on tubular gas condensers used for refining crude coal gas with its high initial content of water vapor, hydrogen sulfide, ammonia, cyanogen, naphthalene and tar. These data were
gathered from commercial plants scattered widely throughout the United States. Professor Kowalke, as a member of this committee, assigned to me the task of trying to calculate and correlate the overall heat transmission coefficients from these data in terms of operating variables, physical properties and gas composition. I was unsuccessful in making any meaningful correlations. Indeed, correlation in terms of the geographical location of the plants seemed to be better than any rational attempt. The decision was made to establish data from carefully controlled operation of a laboratory scale tubular condenser using saturated air-water vapor mixtures under industrial conditions of operation.

In the period 1926-29 few graduate students were enrolled in chemical engineering at the University of Wisconsin. Prior to 1929 only three doctorate degrees had been granted. In guiding research towards a doctorate degree Allan was the only student assigned to me.

A preliminary study of the condensation of water vapor from air saturated at high initial temperatures in a tubular condenser revealed many complexities. Three fluid stream resistances were involved, the air-vapor stream, the condensate layer and the stream of cooling water, besides the resistance of the metal barrier. The heat transfer coefficients of these three streams were to be established each in terms of its independent variables. Because of large variations along the length of the condenser it was evident that coefficients of the individual streams should be determined at short intervals of condenser length. Calculations of average heat transmission coefficients of the vapor stream from usual logarithmic mean values of temperature drops at terminal conditions were meaningless, indeed, the temperature drop at the midsection of the condenser was usually greater than at either terminal. In retrospect, considering the primitive status of scientific information and the complexity of the problem, this investigation would at that time justify three projects with independent approach to each.

A vertical tubular condenser, six feet long, was constructed of three concentric pipes, 3, 7 and 10 inches nominal diameters, well insulated on the outer shell. Cooling water flowed through the inner pipe and saturated air flowed downwards through the two annular channels; the outer outer annular space served as a guard ring together with external insulation to minimize the outward flow of heat. With only $100 available for mechanical help and additional apparatus over a span of three years, the equipment and instrumentation had to be assembled from supplies available in the stock room or borrowed from distressed laboratories, including piping, pumps, thermocouples, orifice meters and potentiometers.

Allan constructed and calibrated all thermocouples and orifice meters. The construction and location of thermocouples were critical for meaningful measurements. Multijunction couples were constructed for measuring average temperatures of the gas stream at each level of cross section. Single couples were located in isothermal areas to avoid errors by conduction. A traveling thermocouple was constructed and installed for measuring the temperature of the cooling water. Temperatures of the three adjoining fluid streams and the central pipe wall were measured simultaneously at successive short intervals of length. Under commercial conditions of operation natural convection predominated in the stream of cooling water; both laminar flow and turbulence occurred in the gas stream; the condensate accelerated from laminar flow to turbulence with rippling at the bottom of the tube.

The measurement and correlation of heat transmission coefficients of fluid streams was in a primitive stage in 1926 when Colburn began his experimental and theoretical studies. Most published experiments had been conducted within the preceding ten years. The most significant work had been carried out in Germany. This appeared in the German language without published translation in English. In the United States chemical engineers required that formulations of transfer coefficients be expressed in terms of molecular properties and operating variables. Other engineers were still satisfied with specific values of overall coefficients and physicists had virtually abandoned the field upon discovering the empirical nature involved. Principles of heat conduction in solids had been well known for over a century starting with the mathematical theory of Fourier in 1822 for the unsteady state. These formulations were extended in the texts of Ingersoll and Zobel in 1913 and by Carslaw and Jaeger in 1921.
Colburn was an ideal student, scientist, and engineer. . . . he had an unusual capacity for clarity of expression . . . (and promoted) self confidence and ambition in others.

The analogy between mass, heat and momentum transfer in flowing fluids was presented by Prandtl in 1910 based in part upon pressure drop formulations of Reynolds in 1874. In England work was reported in 1916 by Pannel for air flowing through tubes and by Stender in Germany for water flowing through tubes. A theoretical equation for the transfer of heat by free convection in fluids was developed by Lorenz in 1881 and greatly improved by Nusselt in 1915. Nusselt in 1910 also pioneered in deriving theoretical equations for the transmission of heat through condensate layers flowing over vertical surfaces and horizontal cylinders.

At the time of Colburn’s studies and just prior thereto five books on general heat transmission appeared in Germany, namely, by Grober (1921 and 1926), by Merkel (1927), Bosch (1927) and Schack (1921). These were then without English translation. The first authoritative book on heat transmission printed in English and applicable to general engineering processes was that of McAdams in 1933 but this book did not appear until seven years after Colburn started his research. McAdams' text and researches generated wide attention to research in heat transmission throughout the United States and among other branches of engineering besides chemical.

Allan proceeded at once to read intensively the German sources relying on his high school instruction and his preparation for absorbing the German language requirement of the doctorate degree. The extraction of complex theoretical principles from lengthy German dissertations required exceptional capacity for intensive concentration. Allan studied the original German sources with intense concentration over long intervals of time to the point of pain and fatigue. Colburn had exceptional capacity for retaining the arguments and voluminous observations of previous investigators with subsequent instant recall. Colburn's genius consisted in this extraordinary capacity for intensive concentration with a mind unusually well organized for retention and retrieval.

In his graduate years Allan devoted fully half of his time to theoretical studies and experimentation related to his thesis over a period of three years. In his efforts to establish simultaneously the principles of heat and mass transfer in fluid streams, condensate layers and water streams with free convection, Allan suffered many periods of despair and frustration especially in his efforts to reconcile his data with the formulations of others. But he always bounced back with a zest for scientific discovery and to infuse the same spirit in others.

From his boyhood days in the recreational area of Northern Wisconsin with its forests and lakes, it was natural for Allan to seek relaxation from his strenuous intellectual pursuits and frustrations in out-of-door sports the year around, in tennis, canoeing, golf, fishing, skating, and iceboating.

In connection with recreation his friend Lou Warrick records a vivid and humorous account of Allan’s discovery of ‘hot ice’. In iceboating together on Lake Mendota their speeding boat struck rough ice and Allan was projected therefrom at high speed over the rough surface on the seat of his pants. Upon recovery Allan feeling his posterior exclaimed, “Gee, Lou, this is the first time I realized that ice can get hot!” Because of the great tragedy in health which befell Allan a few years later few people were aware of his early athletic prowess.

Colburn's computational facilities were limited to the use of the slide rule, to laborious calculations and plotting by hand. In experimental work he received some aid from two seniors working for academic credit, namely Robert E. Zinn and George F. Hrubesky. Today Allan’s monumental task would be greatly facilitated by electronic computers with generous financial subsidies for experimental and computational aid. It should be recalled again that Allan had only $100 available for research aid.

In his graduate years Allan restricted his advanced studies to scientific work related to his thesis. Liberal reading became extra curricular. His advanced studies included a course in heat conduction under Professor Leonard R. Ingersoll, higher mathematics under Professor R. W. Babcock, and advanced chemistry courses under Professors J. Howard Mathews, Farrington Daniels, and John W. Williams. Allan was also fortunate in taking courses under two visiting professors, with the Russian chemist A. M. Frumkin in col-

(Continued on page 193.)
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A. P. COLBURN - A DISTINGUISHED CAREER

ALLAN PHILIP COLBURN was born in Madison, Wisconsin, on June 8, 1904. He graduated from Rhinelander High School and attended Marquette University for two years before completing his education at the University of Wisconsin, where he received his bachelor's degree in chemical engineering in 1926, his master's degree in 1927 and his doctorate in 1929. From 1929-1938, he was engaged in chemical engineering research at the Du Pont Experimental Station in Wilmington.

On May 1, 1938, he became associate professor of chemical engineering and acting head of the University of Delaware's Department of Chemical Engineering. As chairman of the department, he was responsible for developing a wide research program in cooperation with industry and governmental agencies. In 1947 he became Assistant to the President with his chief responsibility that of assisting in the development of research throughout the University. Dr. Colburn was Acting President of the University from April 1, 1950, to November 1950 and, upon the arrival of former President John A. Perkins, he was appointed Provost. At the time of his death in 1955 he was Provost and Coordinator of Scientific Research.

During World War II, Dr. Colburn was instrumental in directing the use of the chemical engineering laboratories at the University on solving war research problems for the National Defense Research Committee, the National Advisory Committee for Aeronautics, the Office of Rubber Reserve, and for various war industries. He further assisted in the direction of war research elsewhere. With Dr. B. F. Dodge of Yale, he prepared the curriculum on chemical engineering for the Army, which was taught in the A.S.T. Program throughout the war years.

In 1948 he was honored as the first recipient of the Professional Progress Award in Chemical Engineering. The award was the first major, general award in the field of chemical engineering. Twelve years earlier the AIChE had given him the Walker Award for outstanding publications.

Active in professional societies, Dr. Colburn was director and chairman of the Awards Committee and chairman of the Publications Committee for the AIChE, on whose council he also served. His memberships included the ASME, for whose Heat Transfer Division he was an advisory associate and former chairman; the ACS, the NEA, ASEE, AAUP, the AAAS, and the Newcomen Society of England. He was a member and former chairman of the Committee on Cooperation with the Military Services for the Engineering Colleges Research Council of the ASEE. In the Delaware Section, ACS, he served as both councilor and member of the education committee. He was an alternate member of the Committee on Chemical Warfare of the Research and Development Board of the DOD.

Honorary societies of which he was a member were Phi Kappa Phi, Phi Lambda Upsilon, Tau Beta Pi and Sigma Xi. He was director of the Delaware Chapter of the American Red Cross, and was a member of the research committee of the Delaware Branch, American Cancer Society. He also served on the research committee of the Delaware Academy of Medicine and was a member of the Delaware Section of the Anti-Tuberculosis Society and the Sigma Phi Epsilon social fraternity.

A nationally recognized authority in chemical engineering, Dr. Colburn was the author of many publications. His papers dealt with heat transfer, fluid flow, distillation, absorption and extracting, and various other technical subjects. He also wrote several textbooks.

While his original interest was in engineering and basic science research, Dr. Colburn appreciated the importance of developing research in the social science area and in broadening the educational programs of students so that they might better understand human relations and international affairs. He was active in developing the University's Institute of Inter-American Study and Research, the Institute for Human Relations, the Marine Laboratories and the evening programs of the Division of University Extension.

As his longtime friend and associate, Dr. Robert L. Pigford, aptly stated, "He was the 'man of all seasons' at the University of Delaware, the prime example for some of us of the uses of scholarship in the fullest way, the best administrator I have seen, the truest friend of student and colleague, the man who makes me remember best that teaching engineering can be just plain fun."

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WHY MATHEMATICS?

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Courses in Applied Mathematics for chemical engineers are relatively recent additions to graduate programs, although some go back about twenty-five years. Often such courses were initiated because of a certain dissatisfaction with pure mathematics offerings and the reluctance of mathematicians to teach topics in applied mathematics. Courses with purely mathematical content should be taught in mathematics departments, while those offered in chemical engineering departments should contain something else. That something else is usually associated with the name “model building,” although if the course is primarily that, it should probably be given as a part of one of the regular engineering science courses. In short, we seem to be speaking here of an offering which neither fits into the regular framework of a mathematics department nor into the regular kinetics, reactor, transport, control, and thermodynamics scheme of the conventional department. In addition to model building, the course must provide instruction in a number of techniques and actually show the student how to solve problems, a feature that is often anathema to the pure mathematician. In this seems to lie the reason for its being. Early courses were primarily exercises in elementary ordinary differential equations with applications to chemical kinetics and oversimplified models of the unit operations. The emphasis is still on differential equations but other topics with a more recent origin are now included.

Our own course has gone through almost a continuous change in the last twenty years and is taken by almost all graduate students throughout their first year in residence. The purpose of such a course is not to make mathematicians of engineers but rather to give the student enough experience that he can better cope with the other graduate courses in the department. Such a course is valuable for the MS student since he may take little other physically motivated mathematics during his one year of course work. For the PhD student it can serve as the first course where significant and complex problems may be solved by advanced techniques and if he has theoretical inclinations frequently urges him on to take more abstruse and rigorous courses from a proper mathematician. As mentioned earlier, our own course has changed considerably through the years and this was forced on us by the fact that new graduate students now enter with a considerably better background than formerly. The average entering student has now had about three years of undergraduate mathematics, some have had four years, and only a few the minimum required for the BS degree. This creates a problem for the instructor, for the class is very heterogeneous not only in terms of quantity of mathematical experience but also because of the fact that in terms of coverage junior and senior mathematics courses can be much more variable than those of the first two undergraduate years. Because of the former I have attempted to give material which will overlap as little as possible with what I think they may have been exposed to. There is an additional problem since many of them are taking advanced mathematics courses concurrently. A number of theoretical and numerical problems are assigned and these seem to be a
departure from mathematical experience of most of the students, and I believe may be the most valuable part of the course. These are graded and returned to the student. For the most part the problems are long and an attempt is made to complement the lectures, bring out points not covered, and to illustrate the numerical procedures and difficulties. Over half of the students do the numerical problems on the University Computer (CDC 6600) although no time in the course is spent on programming. Usually a student will do between 25 and 40 problems in each ten-week quarter. The course is run from 8:00 to 10:00 on Tuesdays and Thursdays (with a five-minute break) and largely as a lecture, although because of the small class size (15-25 students) there are frequent interruptions for questions.

The fall quarter for some years has covered essentially the content of my book on matrices, although not all of the book is covered in any single offering. Sections of the book may be skipped and assigned as reading. Other sections are omitted entirely and this varies from year to year. Chapters 1, 2, and 3 are covered almost entirely along with Chapter 4, through section 4.8; occasionally section 4.12 is presented. Chapter 5 through section 5.14 is in many respects the most important part of the course. A choice is usually made among the sections in Chapter 6, not all of it being given. Chapter 7 through section 7.13 is almost always presented. On rare occasions a shortened version of sections 8.1-8.12 is included. The two volumes of Gantmacher serve as a reference for the course.

All of the material presented in this quarter has a sort of nineteenth-centuryish ring about it and I have thought for some time that it should be modernized, probably in the direction of Shilov’s “Theory of Linear Spaces” and with introduction of material on tensor analysis (covered at Minnesota in the first graduate course in fluid mechanics). This has not come to pass yet, but probably will since the transition to functional analysis would be much easier.

The winter and spring quarters are devoted to an organized exposition of ordinary and partial differential equations with related topics. It is assumed that the student understands the generation of solutions of simple differential equations. Some time is spent on the theory of differential equations covering linear dependence of solutions, existence and uniqueness, and continuous dependence of the solutions on the data. It is important that a student understand the engineering significance of these concepts and what they tell him about a mathematical model, for in the qualitative theory of differential equations these ideas play a central role. A good bit of time is spent on seeking to extract as much information as possible about the solution from the model without recourse to numbers. It is surprising how much information one can obtain for stirred reactors, tubular reactors, simple distillation schemes, heat conduction, diffusion, etc., from the equations by using qualitative but rigorous arguments such as existence and uniqueness and the various maximum principles for both ordinary and partial differential equations. Often all of the intuitively obvious qualitative physical properties of the system can be drawn from the equations and this is the ultimate test of a model. For example, it should not be necessary to compute a solution to prove that a mol-fraction lies between zero and one in a distillation calculation, that in an adiabatic tubular reactor there can be no temperature maximum, or that in an absorption column the transient cannot oscillate.

After this qualitative theory a brief discussion of numerical methods for ordinary differential equations is given covering predictor-corrector schemes and Runge-Kutta methods with applications. The question of numerical stability is briefly discussed since anyone who does a significant amount of computer work eventually runs into stability problems.

At this time a general discussion of the nth order linear differential operator is begun. Most of the interesting problems in ordinary and partial differential equations are boundary value problems. The concept of the adjoint operator and adjoint boundary conditions is introduced and the general idea of a self-adjoint boundary value problem is presented. For example, given the nth order operator $L$

$$Ly = a_n \frac{d^n y}{dx^n} + a_{n-1} \frac{d^{n-1} y}{dx^{n-1}} + \ldots + a_1 \frac{dy}{dx} + a_0 y$$

the adjoint operator $L^*$ operating on $z$ is
Nature operates on inputs to give outputs while mathematical operators, couched in the language of differential equations, operate on outputs to give inputs.

\[ L^*z = (-1)^{n-1} \frac{d^{n-1}}{dx^{n-1}}(a_n z) + (-1)^{n-1} \frac{d^{n-1}}{dx^{n-1}}(a_{n-1} z) + \ldots + \]

\[ - \frac{d}{dx}(a_{n-1} z) + a_n z \]

and it may then be shown if the region of interest of \( x \) is \((a, b)\) that

\[ \int_a^b (zL_y - yL^*z) \, dx = \pi(z, y) \]

where \( \pi(z, y) \) is called the bilinear concomitant and contains the functions \( z \) and \( y \) and their first \((n-1)\) derivatives evaluated at \( a \) and \( b \). In most physical problems we are given \( n \) boundary conditions on \( y \), \( n \) is even, and we have \( n/2 \) boundary at \( x = a \) and \( n/2 \) at \( x = b \) which we assume are homogeneous. Suppose these boundary conditions are denoted collectively by

\[ Y(y) = 0 \]

A fundamental theorem says that there exists a set of boundary conditions on \( z \), called adjoint, unique except for linear combinations such that

\[ \Pi(z, y) = 0 \]

so that

\[ \Pi^*(z, y) = 0 \]

The system made up of the operator \( L \) and the boundary condition \( Y \) is said to be self-adjoint if

\[ L = L^* \]

and

\[ Y = Z \]

\[ \int_a^b (zL_y - yL^*z) \, dx = 0 \]

We consider a self-adjoint eigenvalue problem

\[ Lw = -\lambda p w; \ a < x < b \]

\[ W(w) = 0; \ x = a \text{ and/or } x = b \]

where \( \rho \) is a function of \( x \) and \( \rho(x) > 0 \). \( W(w) \) stands collectively for the \( n \) boundary conditions. There are a number of theorems on the existence and character of the eigenvalues and eigenfunctions of such a system. To be brief, however, there exists a discrete sequence of real eigenvalues \( \lambda_1, \lambda_2, \lambda_3, \ldots \) and a corresponding set of eigenfunctions \( w_1(x), w_2(x), w_3(x), \ldots \) with an orthogonality property

\[ \int_a^b \rho \, w_j \, dx = 0 ; \ i \neq j \]

Provided the set of functions \([w_n(x)]\) is complete with respect to a certain class of functions \( f(x) \) we can expand \( f(x) \) into a series

\[ f(x) = \sum_{j=1}^{\infty} c_j w_j(x) \]

with

\[ c(j) = \int_a^b \rho(x) f(x) w_j(x) \, dx \]

provided the eigenfunctions have been normalized. These two relations play an important role, for if we write

\[ c(j) = \int_a^b \rho f w_j \, dx \]

\[ f(x) = \sum_{j=1}^{\infty} c_j w_j(x) \]

then \( c(j) \) is called the finite Fourier transform of \( f(x) \) and \( f(x) \) is the inverse Fourier transform of \( c(j) \). Without laboring the point here this pair of formulae may be used to solve a number of partial differential equations in an almost automatic way once one recognizes the operator \( L \) and its associated boundary conditions. If a partial differential equation has the form

\[ Ly = \rho(x) M(y) \]

with boundary conditions

CHEMICAL ENGINEERING EDUCATION
All of our problems are physically motivated and the translation of the problem into mathematical terms is not mathematics.

\[ Y(y) = 0 \]

where \( M \) is an operator not containing \( x \) explicitly and having its own boundary or initial conditions. We can write

\[ w_n L y = \rho w_n M(y) \]

and integrate with respect to \( x \)

\[ \int_a^b w_n L y \, dx = \int_a^b \rho w_n M(y) \, dx \]

Using the Green's formula we obtain

\[ -\lambda_n \int_a^b \rho(x) w_n(x) y(x) \, dx = M \int_a^b \rho w_n y \, dx \]

or

\[ -\lambda_n c_n = M c_n \]

This is a system which is simpler since all reference to \( x \) has been removed and may be solved (hopefully) to give \( c_n \) and hence \( y(x) \) by using the inverse transform. In the course this idea is exploited to obtain solutions of a wide variety of diffusion, heat transfer, and reactor problems, and, while, in principle, it is no different than separation of variables, it possesses an automatic quality which appeals to the students.

At this point we also discuss Duhamel's Theorem and the relationship among solutions for impulse, step function, periodic, random, and general inputs, thereby solving the nonhomogeneous problems which have been avoided up to this time. A qualitative discussion ensues showing the difference between mathematical operators and natural operators. Nature operates on inputs to give outputs while mathematical operators, couched in the language of differential equations, operate on outputs to give inputs. For example, a distillation column operates on inputs (feeds) to give outputs (products). The model for a distillation column in the steady state is a system of algebraic relations (which must be inverted) among the outputs. Some mention of non-self adjoint problems is also made showing how the biorthogonal set of eigenfunctions can be used to generate finite Fourier transforms for these problems. However, because of the extreme difficulty of numerical work the problem is not pursued in detail.

Using solutions to problems on finite domains standard limiting procedures may now be used to find Fourier transforms for a variety of boundary conditions on semi-infinite domains (infinite hollow cylinders, etc.). The bag of the student has thus been equipped with a technique which will produce solutions with ease and his confidence is increased. A discussion of the Laplace transform is also included with applications to partial differential equations. This discussion usually takes until about the sixth week of the spring quarter (a total of approximately fifteen weeks).

One of the difficult things about differential equations is that there are no textbooks available intermediate in level between the elementary undergraduate books and books such as Coddington and Levinson, Ince, Hartman, etc. The book by Weinberger is an excellent intermediate book on partial differential equations but there is no corresponding treatment for ordinary differential equations. I have used some parts of Kaplan and Ross but it is surprising that with the number of books on differential equations and the age of the topic there are none that are really suitable.

The remainder of the quarter (5 weeks) is spent in a variety of ways, but for the past two years first order partial differential equations have been presented with applications to chromatography. This is a topic not well-presented in the literature (a lacuna which Professor Aris and I hope to fill). At other times topics such as dynamic programming and calculus of variations, stochastic processes, numerical solution of partial differential equations with stability considerations, continuous models for discrete processes and many others have been presented.

The question arises as to how much rigor should be presented in such a course. The writer has a simple answer to this. Rigor is presented whenever the student feels the need for it. The solution of a partial differential equation involves a series of arbitrary operations and the bright student should ask whether what one obtains really is a solution to the problem. Such a proof requires the introduction of some rigor and it is not avoided. Different representations of a solution frequently arise and the student should wonder whether they are the same; a uniqueness proof is in order here and it is given. Expansions of functions into series require completeness of the set of functions (Continued on page 203.)
OBJECTIVES AND PROCEDURES

The students in the class have done their baccalaureate work in a large number of other schools. Therefore a primary consideration of the course must be the diversity of their preparation, which on each topic ranges from zero through superficial acquaintance to real understanding. The individual students shift between these positions as the topics change. Those who are under-prepared must be given sufficient encouragement and guidance and time for remedial self-study. Those who are over-prepared must at the same time be kept challenged. Ideally each lecture begins from a position of security for the least-prepared and ends at a level which temporarily distresses even the best-prepared. Problems with progressively more difficult parts are assigned. Special readings and problems are suggested for those "who have the time and inclination." The class is at first surprised that these optional problems are discussed as well as the assigned ones, but soon gets the intended message.

Students appear to learn most readily by first examining very simple phenomena and models and then considering the effect of added complexities. Hence the equations, algebraic or differential, for one-dimensional, limiting cases are first derived. Then terms and dimensions are gradually added. Reduction of unsteady state, three-dimensional partial differential equations to simple cases does not appear to achieve the same rapidity or degree of understanding.

I consider it an obligation to demonstrate a convincing and significant application for every model, theory or solution which is presented and to point out the deficiencies and limitations of each model and the uncertainties in the supporting data.

Home problems are assigned corresponding to each class meeting. In addition the students are frequently asked to complete or extend the derivations presented in the lectures. Several longer and optional problems, e.g., to be done on the computer or to be considered as part of the final examination, are assigned during the semester. The students are sometimes asked to prepare an examination question and solution. The problems are a major ingredient of the course and may illuminate a matter barely mentioned in the lectures. The aim is therefore for completion and good comprehension by all students. Teamwork is encouraged with the admonition that anyone who fails to participate as a full partner will ultimately injure only himself.

Incredibly, a few graduate students still arrive without digital computing experience. Hence it is difficult to make full use of the computer in this first course. Optional and group problems are assigned and discussed in terms of computational...
methods when appropriate. The students are encouraged to elect hard-core courses in numerical methods as well as to develop the capability to use the University's computing systems.

The entire semester could easily be spent on any one of the general subjects indicated by the headings below. Some departments of chemical and mechanical engineering do indeed offer up to eight courses on this subject matter—resulting in more complete but not necessarily deeper coverage. However, my general objective is neither to describe the art and equipment nor to cover the literature of heat transfer and fluid mechanics, but rather to present a methodology for interpreting and using data and concepts for the analysis and prediction of chemical and physical processes. The technology of momentum and heat transfer provides convenient and stimulating examples. If a scientific and operational point-of-view is the objective, specific subject matter is of secondary importance and can be chosen primarily for illustrative and motivational purposes. It is amazing how much material becomes redundant when the emphasis is shifted to methods of analysis and solution.

My specific objectives are (1) to give an idea of the character and current state of knowledge in fluid mechanics and heat transfer, (2) to show how to construct and test first-order and better models and (3) to develop capability, motivation and confidence for future self-study.

A textbook is not used in the course. Indeed, a textbook in the classical sense is probably undesirable in any graduate course in engineering. It gives the false impression that the subject is well-known and completely covered. Books at this level, with the exception of a few monograms, invariably purport to cover a wider range of material than the authors have mastered. The students arrive with the false notion that the equations, data and statements in the standard textbooks are almost sacred. Sometimes I use these familiar books as a foil, pointing out errors, inconsistencies and misinterpretations to encourage them to read critically and skeptically.

Readings are assigned in a variety of books and journals. Reference lists are distributed on each topic for optional and future reading to make the students feel that they are scholars rather than mere receptors. I accept and try to implement John W. Gardner's precept that "the ultimate goal of the educational system is to shift to the individual the burden of pursuing his own education." A significant fraction of the lecture material and problems is taken from the very current literature. Notes are distributed in advance for much of the lecture material in order to discourage the frantic transcription of everything written on the blackboard.

A course should evolve from semester to semester in reflection of new developments and concepts in science, engineering and computation and also in response to the changing attitudes and interests of the students. Currently they are concerned about the relevance of their studies. Insofar as possible a response is provided to this demand in the choice of topics and home problems and also by the allocation of some time to the discussion of professional matters. My absences are generally used for quizzes. On returning I usually explain why I was away. This often provokes a discussion of extra-curricular topics.

Tom Baron says a lecture should, like a bullfight, combine grace and excitement. An attempt is made to keep the lectures lively, even at the expense of organization. The students are encouraged to flag me down if they are lost and to challenge me if they are disbelieving.

**COURSE TOPICS COVERED**

**Inertial (Non-Viscous) Flows**

Inertial flow is chosen as a first topic because of simplicity (one-dimensional, algebraic equations are adequate for a first approximation) and because much of the subject is new to most of the students.

Adiabatic and isothermal, reversible expansions and their application to orifices, venturi meters and nozzles are reviewed rapidly. The equations for weak pressure waves (acoustic waves) are derived and applied to the problem of maximum flow through nozzles, including over-expansion and under-expansion, then to the behavior of rocket motors and finally to choked flow in pipes (here including viscous losses).

The equations for gravity, shock and detonation waves, each with reflection, are next developed and applied to open-channel flow, chemical shock tubes and the failure of process equipment, respectively.

**Viscous Flows**

The models and data for the viscosity of gases (including kinetic theory) and of liquids (includ-
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ing non-Newtonian behavior) are examined. One-dimensional material and momentum balances are first derived for laminar flow down inclined planes, inside tubes, etc., then the integral equations for the boundary layer, emphasizing the fortunate insensitivity of the drag to the postulated velocity distribution.

The three-dimensional, unsteady state, partial differential equations for the conservation of mass and momentum are next derived with emphasis on the physical significance of the various terms. Although most students have previously been exposed to this material, they readily admit that they attained no real understanding as undergraduates.

These equations are simplified to some of the cases of laminar flow previously derived in one dimension, and are simplified and solved for a few more complex problems. The Blasius problem is used to introduce the Hellums-Churchill technique for the reduction of partial differential equations. This technique is also used to demonstrate that the equations do indeed describe turbulent flow and that some information on turbulent flows can be obtained by dimensional analysis alone.

Some of the empirical models for the time-averaged turbulent shear stress are examined in a historical framework with emphasis on their success in generalizing the data for the velocity distribution and drag. The various ways of plotting the data for drag in pipes are examined as an illustration of correlation.

Other topics in momentum transfer are considered depending on the available time. (The schedule and hence some of these extra topics are frequently sacrificed for comprehension or for professional diversions which interest the class). Usually flow through porous media and the drag of particles are retained with applications to fluidization, filtration, etc.

Conduction

Models and data for thermal conduction and thermal diffusivity are first examined, including kinetic theory, heterogeneity and mean-free-path effects. The usefulness of the Van Dusen transformation for variable conductivity is noted.

Conduction between plates, concentric cylinders and concentric spheres, and outside spheres and cylinders is reviewed. The equations for three-dimensional, unsteady state conduction are derived. The comparative usefulness of various exact methods such as conformal mapping, the Laplace transform and separation of variables, and approximate methods, such as mapping, bounding and patching, are discussed. The use of Duhamel's formula both analytically and numerically is described.

Numerical methods for both steady and unsteady state problems are developed in limited depth primarily in the hope of whetting the appetite for a complete course in numerical analysis.

Laminar Convection

The integral equations and solutions for the laminar boundary layer and the Graetz solution for fully developed laminar flow in a pipe are examined. (The detailed evaluation of the coefficients and the eigenwerte are deferred to the algebraically eager student as an extra-curricular exercise). The analog of the Graetz solution for a power-law fluid is an example of an extension of a derivation which is assigned as a home problem. Other solutions for laminar flow in a channel under different conditions are examined and compared.

The equations for laminar, free convection are used as an illustration of the power of generalized dimensional analysis to produce the correct form of the solutions and empirical correlations for large Pr, small Pr, uniform heat flux and even fully developed turbulent motion. The success of asymptotic methods in producing first-order solutions of great generality is noted.

The Nusselt equation for condensation is derived and the effects of finite heat capacity, curvature and non-Newtonian behavior are considered in home problems.

Emmon's generalization for condensation, film boiling, free convection and melting is presented as an illustration of the analogous nature of these four gravitational processes and of the great power of first-order analysis.

Turbulent Convection

The one-dimensional empirical models and analogies for turbulent forced convection are compared with each other, with the two-dimensional solutions and with the data. Again, the insensitivity of the solutions to the several pos-
tulates is emphasized as the reason for the surprising success of all of the models.

Radiation

The models and data for emission, absorption, transmission and scattering by solids and fluids are first examined. The integral and differential properties are contrasted.

Interchange between black, gray, adiabatic and specular surfaces is considered. Analytical methods and results (including differential extensions), numerical methods and results, the electric circuit analog and the radiosity formulation are included.

REPRESENTATIVE PROBLEMS

The character and scope of a course are perhaps most evident from the problems which are assigned. Hence, a few representative problems are given below. Because of space limitations these problems are somewhat atypical in that they are restricted to those with very short statements and hence are simpler, involve less input data and are less applied than most of those assigned in the course.

1. A shock wave is generated in a tube containing air at an initial pressure of 0.10 atmosphere and 60 °F. The measured velocity of the wave is 7200 ft/sec. If the wave reflects off the closed end of the tube to what pressure and temperature will the wall be subjected? Note all assumptions.

2. Will adding to the length of the diverging section of a rocket nozzle increase the thrust? Explain.

3. A planar shock wave propagates indefinitely, producing an increase in temperature, pressure and density. What is the source of energy for this compression and heating?

4. Water and n-pentane are pumped at equal volumetric rates between two horizontal parallel plates. Determine the location of the interface for fully developed laminar flow.

5. In cylindrical coordinates the Coriolis force is \( \rho u \) \( \frac{\partial}{\partial r} \) and the centrifugal force is \( \rho u^2 \) \( \frac{\partial}{\partial r} \). Show whether or not each of these terms has a zero or finite, time-averaged value for fully developed turbulent flow in a straight pipe. Do these terms affect the pressure gradients? Explain.

6. On a dry, 70 °F day with a barometric pressure of 740 mm. Hg, a pitcher is able to throw a baseball with sufficient force so that it arrives at the plate 60 feet away with a velocity of 90 miles per hour. Assuming that he throws with the same force, what would be the maximum and minimum velocities at the plate if all combinations of weather from 40 °F to 100 °F, zero to saturated humidity and 730 to 760 mm Hg were encountered during the season? Neglect the effect of ambient conditions on the ball itself.

7. A large block of copper at 100 °F is brought in contact with a large block of steel at 200 °F along two plane faces of the blocks. Calculate the temperature of the interface as a function of time.

8. The mean monthly air temperature at Detroit varies as follows in °F: J, 29; F, 28; M, 37; A, 48; M, 57; J, 63; J, 65; A, 65; S, 62; O, 54; N, 43; and D, 32. Assuming that the surface temperature equals the air temperature and that moisture, curvature and geological effects may be neglected, calculate the temperature at a depth of 10 feet as a function of time. The soil may be assumed to have a specific gravity of 1.75, a thermal conductivity of 1.4 \( \times \) 10\(^{-3}\) cal/cm·sec·°C and a specific heat of 0.25.

9. Starting with the general integral formulation, derive a numerical value for the asymptotic Nusselt number for fully developed laminar flow and a fully developed temperature field in a circular tube with a uniform heat flux density at the wall.

10. Determine by dimensional analysis alone the minimum functional relationship between the local heat transfer coefficient and the other variables for laminar, steady, free convection of a power-law fluid to a vertical plate at uniform temperature. The usual assumptions of boundary layer theory may be employed and the inertial terms may be neglected.

11. Experimental data are to be obtained for convective heat transfer and pressure drop in smooth pipes. Experience suggests that for the chosen conditions, \( (hD/k)/(C_{pr}/k)^{1/3} \) and \( (-dP/\Delta L)(D_p/G^2) \) can be expected to be different functions of \( DG/\mu \) only. Suggest dimensionless coordinates for a graphical correlation of the measured heat transfer coefficient as a function of the measured pressure gradient such that neither coordinate contains the velocity.

12. A reaction in a very viscous material is to be carried out in a scraped-surface heat exchanger. The heat of reaction and heat of viscous dissipation may be neglected. It is proposed to double both the length of the exchanger and the flow rate. Will be conversion be greater, equal or less? Why? Will the outlet temperature be greater, equal or less? Why?

13. Calculate the error resulting from the following approximation for the interchange factor between a square surface and a parallel differential surface at a normal distance equal to the side of the square. Subdivide the square into four square elements and sum the interchange factors for these elements using the center points only.

14. A cloud reduces the radiant flux from the sun by 40%. Estimate the reduction to be obtained if the thickness of the cloud were tripled (a) assuming absorption and negligible scattering (b) assuming scattering and negligible absorption.

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Many colleagues, including particularly R. R. White, J. O. Wilkes and D. A. Saville, and many, many students at both the University of Michigan and the University of Pennsylvania have contributed to the development of the philosophy and details of this course.
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Fluid dynamics plays a central role in many problems of interest to chemical engineers. Because of this, the semester course in the area presented by the ChE Division of the University of Illinois has been one of the most durable offerings in its graduate curriculum. I have taught this course since 1953 and one similar to it had existed many years prior to my involvement.

My goal is to present a unified treatment of fluid dynamics to students who have had courses in differential equations and transport phenomena and who have some knowledge of vector notation. The content reflects the philosophy within the Division that the more advanced and more current aspects of any field are covered in our Special Topics courses and in our seminars. (For example, in recent years I have conducted seminars on turbulence, hydro-dynamic stability, continuum mechanics, water waves, numerical solutions of the equations of fluid mechanics, rheology and in modern aspects of boundary layer theory.) As a result, the fluid dynamics course is largely based on material available in a number of textbooks. It is intended that it be a starting point for advanced studies of the current literature, which are best done in an informal fashion.

At present, the course is in transition because of the introduction by most schools of more advanced topics in fluid dynamics at the undergraduate level. One of my chief difficulties is to assess properly the background of the students since I find that the courses offered at different universities in transport phenomena vary considerably in content and depth. Therefore, at the risk of losing the interest of the better prepared students, I give a rapid treatment of key physical notions that should be covered in a basic course in transport phenomena. I also give the students a chance to do some reviewing of their own by assigning at the beginning of the course a number of problems from the book “Transport Phenomena” by Bird, Stewart, and Lightfoot.

Thomas J. Hanratty is professor of chemical engineering at University of Illinois. He was educated at Villanova, Ohio State, and Princeton University, PhD ('53). His recent professional honors include the Curtis W. McGraw Award (ASEE) and the William H. Walker and the Professional Progress Awards of AIChE.

I have been experimenting with the contents of the course and, as a result, the outline accompanying the article is meant to represent the types of topics treated and not the total material covered in a semester. For example, this past year I did nothing with topic 10 and only partially covered the notes I have prepared under topic 9. One of the ideas that is not sufficiently developed is that of hydrodynamic stability. I am currently giving some thought to ways of working it into the course.

BASIC EQUATIONS

The course is initiated by reviewing the concept of a fluid particle and of a continuum and, in particular, by pointing out circumstances, such as the settling of fine particles, where the continuum model is invalid. It is then indicated that an Eulerian framework is usually more convenient than a Lagrangian framework for solving fluid dynamical problems. The second law of motion and the first law of thermodynamics are reformulated so that they are applicable to an arbitrary fixed volume in space rather than to a fixed mass. Difficulties that sometime can be encountered in applying thermodynamics, which is formulated for an equilibrium system, to flow fields are pointed out.

UNIDIRECTIONAL VISCOUS FLOWS

The concepts of a shear stress and the sign convention to be associated with it are introduced by considering fully developed flow in a pipe. New-
ton's law of viscosity is initially presented by assuming that the shear stress is directly proportional to the velocity gradient. Through the momentum theorem it is pointed out that the shear stress may also be interpreted as a flux of momentum. Through this concept kinetic theory can be used to interpret fluid viscosity. Flow between circular cylinders is considered because it is a convenient way to introduce concepts which are used later to extend Newton's law of viscosity to three-dimensions. It is pointed out that viscous effects will not depend on that portion of the velocity gradient that gives rise to solid body rotation but will depend on that portion which distorts the shape of fluid area elements.

NON-NEWTONIAN FLUIDS

Experiments are described which illustrate non-Newtonian behavior and which yield definite properties characterizing the rheological behavior of fluids. These include nonlinear dependence on the rate of strain of the fluid, normal stress effects caused by shear flow, and elastic effects. The Rabinowitsch equation is developed either in class or in a homework problem because of its importance in interpreting nonlinear effects in steady flows. Methods for calculating normal stress coefficients and the use of small amplitude sinusoidal oscillations and relaxation tests to determine elastic properties are discussed. The Maxwell equation for linear viscoelastic fluids is applied to a few simple flow problems.

EQUATIONS OF MOTION

The differential equations describing the three-dimensional flow of a Newtonian fluid are now developed in a cartesian coordinate system. This is not done in general curvilinear coordinates because the small number of new physical concepts introduced by this generalization does not seem to warrant the added complexity. The equation of conservation of mass and the momentum theorem are applied to a differential volume. The use of cartesian tensors to simplify the notation is introduced. The physical interpretation of the substantial derivative arising from the momentum terms is presented. It is pointed out that in order to describe the force acting on the surface of a volume the location as well as the orientation of each surface element is needed. The problem of representing these surface forces is greatly simplified by showing that the stress on any arbitrarily oriented surface element can be described in terms of the nine stress components needed to specify the stress vectors acting on three mutually perpendicular planes. Cauchy's equation of motion can then be derived. The properties of the stress components are now explored in order to facilitate the development of constitutive relations. It is shown that the nine stress components are a second order symmetrical cartesian tensor. The concepts of principle axes and principle stresses are introduced. The invariants of the stress tensor are defined.

CONSTITUTIVE RELATIONS

The constitutive equations relating the stress components to the velocity field are now developed for a Newtonian fluid. The problem of doing this for more general fluids is discussed briefly. The velocity gradient is shown to be a second order cartesian tensor which can be represented as the sum of a symmetric and an antisymmetric tensor. The stress components can be related only to the symmetric part of the stress tensor (rate of strain tensor) since this is the part that gives rise to the distortion of fluid volume elements. Newton's law of viscosity is generalized to three dimensions by assuming that the components of the stress tensor are only functions of the components of the rate of strain tensor. This produces eighty-one coefficients of viscosity. Only two of these coefficients are independent, because the fluid is isotropic and because the stress and rate of strain tensors are symmetric. The assumption of a linear relation between the stress tensor and the rate of strain tensor is now relaxed and the most general relation is developed for an isotropic fluid for which the components of the stress tensor are only functions of the components of the rate of strain tensor. This relation predicts normal stress effects and non-Newtonian behavior for steady flow in a channel. The work of Oldroyd, Rivlin and Erickson, and Colman and Noll aimed at developing constitutive relations which exhibit elastic effects as well as nonlinearity and normal stresses is discussed only qualitatively.

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by introducing the constitutive equations for a Newtonian fluid into the Cauchy equation. The solutions of these equations for the case of an incompressible fluid are developed for three very general assumptions: creeping flow, perfect fluids, and boundary layers.

CREEPING FLOWS

According to the creeping flow approximation the inertia terms of the equations of motion can be neglected at small Reynolds numbers. Creeping flow around a sphere is worked out in much detail since it illustrates the use of a stream function, the method of eliminating the pressure term from the equations of motion, and the calculation of body forces and skin friction on a solid body. The case of flow around a bubble is worked out in a homework assignment. It is shown that the creeping flow approximation does a good job in predicting the force on a sphere but a poor job in predicting the flow field at distances far from the sphere. For flow around a cylinder it doesn't even predict the force on the cylinder. Regular perturbation methods are shown to yield poor higher order approximations to the creeping flow solutions. The method of Oseen is discussed. The singular perturbation method, as outlined by Proudman and Pearson, is then shown to be a proper way of getting higher order approximations.

PERFECT FLUIDS

A perfect fluid is defined as one for which the viscosity and thermal conductivity are zero and for which the entropy of fluid particles is constant. The Euler equations then describe the flow field. The conditions under which one might expect an irrotational flow field are discussed. The velocity vector is then describable as the gradient of a potential function and the velocity field is given by the equation of conservation of mass. The integration of the Euler equation using the assumption of irrotational flow yields the Bernoulli equation. The Bernoulli equation can also be obtained for rotational flows by applying the momentum theorem to flow of a perfect fluid along a stream tube. The constant of integration then varies from stream tube to stream tube. The solution for the flow of an irrotational perfect fluid around a sphere is obtained. The predicted pressure distribution around the surface is discussed. The concept of virtual mass is introduced by considering the unsteady motion of a sphere in a perfect fluid and is applied to some problems of interest. Two-dimensional flows of irrotational perfect fluids are then considered. A stream function can be defined for a two-dimensional flow from the equation of conservation of mass and complex variable theory can be used to solve flow problems. A number of examples are considered including the lift of solid bodies and free streamlines. The treatment of small amplitude waves at an interface is one of the more successful applications of the theory for irrotational perfect fluids. Some of the problems considered in this area are progressive two-dimensional waves, standing waves, group velocity, wave resistance, Kelvin-Helmholtz instability, and Taylor instability.

BOUNDARY LAYERS

Boundary layer theory attempts to correct perfect fluid theory for viscous effects by assuming the existence of a viscous layer close to a solid surface. If this viscous layer is thin compared to the dimensions of the body a simplified version of the Navier-Stokes equation applicable to boundary layers on flat plates and curved surfaces is obtained. The concept of separation is discussed and it is pointed out that boundary layer theory is only applicable up to the point where the boundary layer separates from the solid surface. The difficulties of applying the theory are discussed, and, in particular, the problems associated with determining the external inviscid flow or the pressure distribution around the body are emphasized. Dimensional analysis is applied to the boundary layer equations to determine the functional relation between the skin friction coefficient and the Reynolds number. Similarity solutions are briefly discussed. The series methods of Blasius and of Görtler and the integral methods of Pohlhausen and of Bohlen and Walz for solving the boundary layer equations for some general pressure distribution are introduced. I find that the best way to present these methods is to give a homework problem which requires the application of boundary layer theory to a solid body for which the pressure distribution is known.

TURBULENCE

This treatment of boundary layers concludes my discussion of laminar flows. It might seem anomalous that even though most flows in nature are turbulent I don't introduce the topic of tur-
bulence until this point in the course. The reason for this is simply that a theory for turbulent flows is still to be developed. Therefore my goal in treating turbulent flows is to introduce some of the language used in correlating turbulence measurements and in characterizing the turbulent field. The increased apparent shear stress in turbulent flows is explained in terms of the momentum transport caused by the fluctuating velocity field. The concepts of eddy viscosity and mixing length are introduced. They are found not to be as useful for turbulent flows as were molecular viscosity and mean free path for laminar flows because the scale of the turbulent motion responsible for transport is of the same order as the dimensions of the field. A general discussion is given on the character of fully developed velocity profiles and, in particular, on the roles of fluid viscosity and of the viscous sublayer. The variation of the average velocity and the eddy viscosity with location is correlated through dimensional analysis and the “law of the wall”, the “velocity defect law”, and the “overlap law”. It is then shown how the definition of eddy conductivities for heat transfer are useful in explaining measurements and in particular the effect of Prandtl number on temperature profiles. The interpretation of fully developed velocity profiles and Cole’s “law of the wake” are used to develop predictive methods for general turbulent boundary layer flows. Taylor’s treatment of point source diffusion in homogeneous turbulent fields is presented as one of the few successful theories in turbulence. It is used to explain the gross aspects of turbulent mixing and to interpret the observed variation of eddy conductivities. Statistical methods for describing turbulent flows are discussed and in particular the concepts of correlation, scale, and spectrum are introduced. A very brief summary is given of theoretical attempts to deal with turbulence through the use of the concept of isotropy and the definition of a turbulence structure.

COMPRESSIBLE FLOWS

The last topic in the outline is a one-dimensional treatment of compressible flows. It is usually presented after the material on perfect fluid theory but appears here in my outline because in recent offerings of the course I have deleted it. Most of this material with the exception of that on finite amplitude waves and shock tubes are more properly treated in undergraduate courses.

OTHER APPROACHES?

I should conclude this article by saying that the course that I have discussed is only one way, and not necessarily the best way, of introducing graduate students in chemical engineering to basic concepts in fluid dynamics. My own introduction to and interest in fluid dynamics developed from a course in reactor design.

FLUID MECHANICS COURSE OUTLINE

1. Basic Equations
2. Unidirectional Viscous Flows
3. Non-Newtonian Fluids
4. Equations of Motion for a Viscous Fluid
5. Constitutive Relations
6. Creeping Flow Approximation
7. Perfect Fluid Theory
8. Boundary Layer Theory
9. Turbulence
10. One-Dimensional Compressible Flows

The following item on CACHE was submitted by Professor Warren D. Seider, University of Pennsylvania, Philadelphia, Pennsylvania 19104.

The CACHE (Computer Aids for Chemical Engineering Education) Committee has been organized to coordinate the development of computing systems for use in chemical engineering education. The committee includes twenty educators from sixteen universities. The principal goal of the CACHE Committee is to accelerate the integration of computing into the chemical engineering curriculum by sustained inter-university cooperation in the preparation of curriculum and course outlines and in the specification and creation of computing systems.

The CACHE Committee's curriculum subcommittee has organized a session for the AICHE Annual Meeting in Washington, D.C., entitled “Computers in Chemical Engineering Education.” The session will emphasize topics relating to short and long range plans for the integration of computers into the curriculum. Ten members of the CACHE Committee will participate in the panel discussion after brief presentations.
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The theory of transport processes in the past twenty years has been developed into a comprehensive scientific basis for the description of the essential operations of chemical engineering in any arbitrary differential volume element. The theory is essentially a continuum theory which poses differential equations which must be integrated over the domain pertinent to each particular process unit under consideration. Two major difficulties arise in application. The less onerous is the fact that continuum theory does not provide the values of the transport properties, equations of state and constitutive relationships for specific systems. Molecular statistical mechanics or experimental measurements, or both, must provide this data. The more serious is the extremely intricate forms often taken by the solutions of the transport equations, for example, in turbulent flow. Although turbulence has been studied intensively for nearly 100 years, we still lack a sound theoretical connection with the Navier-Stokes equations and still less a predictively useful one. The principles of fracture under stress are equally important in crushing and grinding operations and are even less well understood in terms of elasticity theory. Aggregation, coagulation and agglomeration are likewise processes which cannot as yet be usefully described by fundamental transport theory.

All of these processes have in common the circumstance that they occur under conditions which permit a large variety of solutions of transport equations and which select no one of this variety uniquely. The flow paths in a stirred vessel, each of which we are confident is a solution of the Navier-Stokes equations, are so various that we must describe them as a statistical aggregate of paths having some probability distribution. In most applications, the residence times determined by each path are of less interest than the mean residence time, or some other statistical property of the residence time distribution. In some cases, however, the distribution itself is of direct interest, as in a crystallizer, since here the crystal size distribution is a direct consequence of the residence time distribution.

Thus, there is a class of unit operations for which the basic transport equations are insufficient to provide the theory for engineering design. The first stage of improvement over direct empiricism and analysis by dimensionless groups is to pose a theory based on a statistical distribution of possible transport processes. The system in question is defined by a number of properties (or state variables) whose values are subject to stochastic variation. We visualize the possibility of making a simultaneous observation of these properties and believe that, in any sufficiently large set of replicated observations there will be a definite frequency with which any specified set of values will be observed. The function of the state variables which associates this probability with the specified set of values is the probability distribution.
The flow paths in a stirred vessel, each of which is a solution of the Navier-Stokes equations, are so various that we must describe them as a statistical aggregate of paths having some probability distribution.

For example, in an ideal gas the velocity of any particular molecule might (in thought at least) be observed. Repeated observations will not give the same result, but the observations will tend to cluster about a central value. We can define a function $P(v)$ which is the probability that the observed value, $v'$, be at most equal to $v$, i.e.,

$$P(v) = \text{Probability that } v' \leq v = F(v) \quad (1)$$

Our fundamental physical hypothesis is that repeated observations define in the limit a definite function $F(v)$. In general, of course, $F(v)$ may be multi-dimensional, even continuously infinite dimensional, but the conceptually simple cases of one to three dimensions are often of real utility.

Our knowledge of the probability $P(v)$ is not limited solely to the results of empirical observation. We remain convinced that the transport equations hold for sufficiently local phenomena just as any one molecule in a gas obeys Newtonian (or quantum) laws of motion. Hence, the variations in the values of the state-variables must be consistent with the local transport laws and their distribution function, $P(v)$, is not purely random. There must be correlations imposed by the local laws which lead to functional relationships between the statistical properties of the system and which account for the central tendencies of the distribution of state-variables. Indeed, they should determine the functional form of $F(v)$ itself.

The role of statistical theory is to discover and define those classes of distribution function which are consistent with the local transport laws and whatever other conditions are required and can be defined by the physical nature of the process under study. These additional conditions are usually such physically obvious requirements as, for example, that the system is confined to a finite volume, or contains a fixed mass, or has a definite average velocity and/or energy. Since local velocity is a distributed variable, the requirement that the system have an average energy requires that $F(v)$ have a form that will produce a definite mean square velocity

$$\langle v^2 \rangle = \int_{-\infty}^{\infty} v^2 dF(v) \quad (2)$$

Thus physical considerations will restrict the class of admissible distribution functions to those possessing at least one and usually two moments, or more.

In addition, the effect of the local transport laws on the distribution functions can be expressed very generally. For the simple case of a single stochastic variable, $q$, whose local rate of change is $\dot{q}(q, t)$, a continuity equation holds in the form

$$\frac{\partial f}{\partial t} + \frac{\partial (qf)}{\partial q} = H(f, q, q', t) \quad (3)$$

Here $H(f, q, q', t)$ is a function that expresses the effect of random sudden interactions upon the distribution density $f$. Two classes of system are met with in applications. In one, the elements of the system interact only rarely, as in kinetics, or not at all, as in collisionless plasmas or non-agglomerating crystallizers. Changes in $f$ are then brought about by the influence of external fields on the motion of the non-interacting particles, modified by occasion strong interactions (or collisions) between particles. In the second class of system, a particle interacts frequently with others, but weakly, so that each collision produces only an infinitesimal modification of its properties, as in Brownian motion, or in plasma dynamics.

In the first case, one estimates the change in $q$ produced by the strong interaction in a collision and sums over the distribution of target particles and impinging particles. The function $H$ then is the net probability that in unit time a particle acquire a value of $q = q' + dq$ by interaction with other particles. It will usually be expressible as a collision frequency multiplied by a cross-section and integrated over the distributed property, $q$.

In the second case, the effect of collisions is to produce an infinitesimal change in $f$ and the $H$ function is expanded in series of derivatives of $f$ with coefficients which depend upon the collision dynamics.

In recent engineering applications, physical particles have been envisioned and the "particle balance equation" has been a descriptive term. In
general probability theory, the Chapman-Kolmogoroff equation is studied, usually under restrictions slightly more limiting than desirable for engineering applications.³

Physicists have studied the Fokker-Planck or Boltzmann equations⁵ (or for aerosols,⁶ the Smolichowski equation) in theories of molecular statistical mechanics.⁷

The Liouville equation clearly applies to any stochastic system for which one can define the weakly interacting entities, or generalized particles, and the significant state-variables, q, and their local laws of motion, q = Q(q,t). When physical particles are the elements of the system, f can be interpreted directly as the particle number distribution in q, which may be taken to be location, size, mass, residence time or other measurable or significant property. However, in polymers,⁸ one can define chain segments and a distribution of chain lengths which obeys the balance equation. For all termination schemes except radical recombination, or branching transfer, the collision term, Η, vanishes and the chain length distribution is determined by the rate of growth in a monomer field, modified by catalysts and transfer agents. Chemical kinetic laws thus give us forms for f = Q(q) and where required, for Η(q,t). In comminution⁹ the same equation is obeyed, but now q (size) is altered only by impact collision. The present problem here is discover the appropriate fracture equations for individual particles so that an expression can be given for Η(q). In aerosol coagulation, the collision mechanisms are well defined but the effects of boundary conditions and external fields have been explored only partially.

That there is a pedagogically useful common base for this wide variety of applications was evident in a seminar conducted recently at Northwestern University in the Winter Quarter, 1968-69. Graduate students and faculty interested in crystallization, polymerization, aerosol coagulation, hydrosol coagulation and reaction kinetics in dispersed two phase media participated. The ostensible outline of the seminar was afforded by Beran, “Statistical Continuum Theories,” but it soon became apparent that some background in basic probability was required and several weeks were spent by the author developing the basic probabilistic notions, the Chapman-Kolmogoroff equations and the Liouville or Fokker-Planck Equations as applied to simple Markov processes. The books by Feller, “Introduction to Probability Theory,” Vol. I and especially Vol. II were invaluable in this phase of the seminar. Blanc- LaPierre and Fortet, “Theory of Random Functions,” was also very helpful in providing physically motivated treatments of probability theory. Loeve, “Probability Theory,” is a standard reference on matters of rigor and mathematical detail.

The following topic headings suggest the scope of the course. Each occupied three to five lecture periods.

2. Concepts of probability theory—distribution, mean, conditional probabilities, set functions, combination of probabilities.
3. Characteristic functions, moments.
4. Random functions, indicator function.
5. Law of Large Numbers—Tchebycheff inequality, Poisson distribution—Central Limit Theorem.
6. Standard probabilistic models—Bernoulli trials, compound events, normal distribution.

The final eight days were devoted to reports on specific applications to fields of interest to the participants.

As the seminar developed, it became increasingly apparent that much of the engineering literature in probabilistic models consists of rediscovery or reinterpretation of some basic concepts and models which have been thoroughly studied in general theory, but which need to be made explicit and in some cases extended to cover fields of engineering interest. Most discussions of random processes are based on Markov processes, yet many engineering models are non-Markov. Some may be considered to be superpositions or convolutions of Markov processes, and this representation is often illuminating when one discovers it.

Of greatest value, perhaps, was the exercise in the use of probabilistic concepts and the demonstration of a common logical structure in a wide range of seeming independent physical phenomena. An initial insight was gained into the
identification of properties of a system which are purely consequences of its being an assembly of weakly interacting parts or particles as distinguished from those which reflect the intrinsic physical nature of the isolated particles.

It seems to the author that while such insights depend upon understanding the general theory of stochastic processes, they do not come without deep study and comparison of specific processes. Therefore, the statistical theory of particulate systems is truly an engineering science, approachable in a useful way from the base of the analysis of engineering problems.

REFERENCES


HOUGEN ON COLBURN (from p.171.)

Iodial chemistry and Peter Debye in the kinetic theory of gases.

AFTER SECURING HIS DOCTORATE degree in 1929, Colburn was employed in the Engineering Experiment Station of the E. I. Du Pont de Nemours Company under Thomas H. Chilton. The du Pont Company very generously supported Allan in his undertaking to derive independently the mathematical formulations for mass and heat transfer in fluid streams covering a wide variety of industrial devices and conditions. These formulations appear in Chapter VII of the pioneer bulletin “Studies on Heat Transmission” by Colburn and Hougen [Bulletin 70 of the Engineering Experiment Station, College of Engineering, University of Wisconsin, October 1930]. Otherwise this bulletin is based on Colburn’s doctorate thesis. The rough draft was improved by the critical review of K. M. Watson.

Colburn was an ideal student, scientist and engineer. In conversation and public lectures he had an unusual capacity for clarity of expression. He met unsound criticisms and arguments of his audience with patience and encouragement, never with disparagement, seeking not personal acclaim but rather promoting self confidence and ambition in others. My technical correspondence with Allan continued for fifteen years following his academic career but terminated when I no longer could keep pace with his ever expanding scientific speculations.

My last meeting with Allan occurred in London in September 1951—an unexpected meeting at the time of the Festival of Britain. Mrs. Hougen and I met Mrs. Colburn accidentally on a London bus on our way to the Tate Art Gallery. Allan arrived in London one week later while we were awaiting boat reservations for a return trip to the United States. The four of us spent a pleasant summer evening together at the amusement section of the Festival of Britain. We enjoyed watching the teenagers on the roller coasters and whirligigs. In turn the British teenagers enjoyed our strange use of the English language.

As an epilogue to this sketch I should add one additional incident. In the fall of 1963 a young coed, Miss Nancy Hall, a graduate student and research assistant in the Department of Oncology at the University of Wisconsin came to my office to inquire about the possibility of a young man, Willis Colburn, entering the University of Wisconsin as a Senior in Electrical Engineering. This was easily arranged. When Willis appeared on the campus, his similarity to his father 40 years previous was most striking and brought a surge of nostalgic memories. And thus this account returns full circle to its beginning, starting with a meeting with Allan and his father Willis in 1922 and ending with the enrollment of his son Willis 42 years later. Nancy and Willis were soon married. Both continued as research assistants and graduate students for two or three years in their respective fields. And thus three generations of Colburns have touched my life over 46 years of time. I understand the fourth generation has recently arrived.

I shall close with one sentence from the letter of his college friend Louis Warrick “How proud the parents (of Allan Colburn) would be to know of this latest honor to the memory of an outstanding son.” This applies to all who knew Allan Colburn.

FALL 1969
A Course in Mass Transport
DIFFUSIONAL OPERATIONS

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This is an introduction to heat and mass transfer for graduate chemical engineers and others seriously interested in transport phenomena. It is normally given in the spring semester to provide entering students an opportunity to take intermediate transport phenomena or fluid mechanics by way of preparation. It can be followed to advantage by special topics courses offered on an irregular basis and by Professor Curtiss' course, The Transport and Other Properties of Fluids, given in our Chemistry Department.

The organization of the course is indicated in the idealized outline of Table 1, but the actual coverage has changed substantially from term to term ever since its original ancestor in 1944 was introduced by Olaf A. Hougen. Emphasis is normally given to those topics in greatest need of reorganization. Thus in 1965-66 and 1966-67 emphasis was put on the formulation and solution of multicomponent diffusion problems and the estimation of transport properties of low-density gases. During the last two years the highest priority has been given to applications of boundary-layer theory, with particular emphasis on mass transfer across mobile interfaces. This current bias shows clearly in this paper. It is now our hope to decrease the emphasis on transport properties, and, if possible, to put this material in a separate course. If this goal is realized, more attention will be given to applications of current interest, to demonstrate the utility of the techniques introduced.

The direction in which this course changes will, however, be strongly influenced by the instructor in charge since course content and the instructor's research program have always been closely interrelated. Until recently the coverage was heavily influenced by Mr. Lightfoot's interests in biomedical mass transfer and fluid-fluid contacting devices. With the increasing involvement of Mr. T. W. Chapman more emphasis on electrochemical applications can be expected.

Professor Lightfoot was educated at Cornell University, BchE and PhD. In 1953 he joined the Wisconsin department, became active in curriculum revision, and collaborated with Bird and Stewart on the text Transport Phenomena. His major research interests are in mass transfer and separation processes and in the application of transport phenomena to environmental and biomedical problems.

There is no one reference on which this course is based. However, the text Transport Phenomena provides a good introduction to much of the material covered, and The Molecular Theory of Gases and Liquids is used very heavily for both the phenomenological aspects of diffusion and the prediction of transport properties. It has also been the custom in recent years to distribute copies of the lecturer's notes, and a substantial portion of these is now available in printed form as Chapter Two: Estimation of Heat and Mass Transfer Rates in Volume 4, Lectures in Transport Phenomena of the AIChE continuing education series.

SUMMARY OF PRESENT COURSE

I. The Equations of Change and the Transport Properties

The purpose of this first section of the course is to lay a sufficiently firm theoretical foundation for the foreseeable needs of the students. It has been found desirable to spend six to eight weeks on these topics, or eighteen to twenty-four 50-minute class periods, and even then only a partial coverage can be achieved. In the spring of 1968-69 most of the material on transport properties was omitted to permit greater coverage of boundary-layer theory. However, it is felt by the author that this material should not be slighted.

Our introduction of the conservation equations
TABLE 1—Topical Outline for Diffusional Operations

I. The Equations of Change and the Transport Properties

A. Conservation Relations for Multicomponent Systems
   1. The equations of continuity and energy
   2. The equations of motion
   3. The equation of entropy conservation

B. Relations between Fluxes and Driving Forces: The Transport Properties
   1. A thermodynamic basis for the formulation of rate equations
   2. Prediction of transport properties on the basis of kinetic theory
   3. Semi-empirical correlations of the transport properties
   4. Experimental determination of transport properties

C. The Requirements of a Quantitative Description
   1. Review of the equations and boundary conditions needed to describe mass-transfer systems
   2. Dimensional analysis
   3. The approximate description of multi-component non-isothermal systems in terms of binary isothermal solutions

II. Estimation of Heat and Mass-Transfer Rates in Well-defined Systems

A. Intraphase Transport in Systems of Fixed Geometry
   1. The film model: unidirectional transport
   2. Convective heat and mass transfer through laminar boundary layers
      a. Forced convection
      b. Free convection
   3. The effects of operating conditions on intraphase transfer coefficients
      a. Net mass transfer across bounding surfaces
      b. Homogeneous chemical reactions
      c. End effects

B. Intraphase Transport in Systems with Mobile Interfaces
   1. The boundary-layer equations of energy and continuity near a deformable surface
   2. Description of model systems
   3. Effects of operating conditions

C. Interphase Transport
   1. Addition of intraphase resistance: the two-resistance theory of Whitman and its limitations
   2. Effects of heat and mass transfer on hydrodynamic stability: Marangoni effects

III. Approximate Descriptions of Complex Systems

A. Mass Transfer to Rippling Laminar Films
   1. The effect of surface mobility on mass-transfer effectiveness
   2. The effects of surface-tension gradients on heat and mass transfer

B. Mass Transfer across Free Turbulent Surfaces

C. Mass Transfer in Dispersed Systems: Performance of a Model Liquid Extractor

The rate equations require a much more extensive discussion, however, and neither the coverage nor the approach of Transport Phenomena is considered adequate for our purposes. We begin with a careful description of the postulates and predictions of irreversible thermodynamic analyses and put major emphasis on the mass-transfer aspects. The most important single result of this discussion is the generalization of the Stefan-Maxwell equations which for isothermal transport take the form:

\[ \frac{\partial x_i}{\partial t} + \nabla \cdot (D_{ij} \nabla x_i) = 0 \]

These equations define the multicomponent diffusivities. Equation 1 forms a very convenient and flexible basis for discussion of diffusional transport in both free solution and mechanically constrained membranes. It is particularly useful for systems containing electrolytes.

Discussion of kinetic theory is largely a condensation of the pertinent sections of the Molecular Theory of Gases and Liquids, and its purpose is to explain the origins of the low-density gas expressions summarized in Chapters 1, 8, and 16 of Transport Phenomena. This is difficult material to explain in a short time, particularly in the later highly mathematical stages of the development of expressions for the transport properties. We are still looking for easier ways to "tell the story". Nevertheless this portion of the course has proven useful to the students and has stimulated a number to take Professor Curtiss' course in transport properties referred to above.

Subsection C is rather heterogeneous and includes such topics as the specification of boundary conditions at gas-solid and fluid-fluid interactions, development of scale-up criteria, and solution of multicomponent diffusion problems by matrix techniques. Here too it is important for the lecturer to focus attention on carefully selected areas rather than to attempt encyclopedic coverage.

\[ \nabla \psi \cdot \mathbf{v} = \sum_{i=1}^{n} \left( \frac{\partial \psi_j}{\partial x_i} \right) \nabla x_i \]

*Here \( \psi_j \) is the molar chemical potential of species \( j \), and except as noted the nomenclature of this article is that of the text Transport Phenomena.
II. Estimation of Heat and Mass Transfer Rates in Well Defined Systems

Accurate prediction of heat and mass transfer rates in applications of practical interest is still a formidable problem. This is due in part to the complex geometry and flow conditions encountered but also to the large number of parameters affecting system behavior. Fortunately it is often possible to determine the functional dependence, and even the magnitude, of heat and mass-transfer coefficients from highly simplified models of the real system. This section of the course is devoted to discussion of the most widely useful physical models.

A. Intraphase Transport in Systems of Fixed Geometry

We start by discussion of intraphase transport in systems with fixed boundaries and concentrate on asymptotic boundary-layer models. In each case we begin our discussion with a simple prototype to illustrate characteristic behavior and then proceed to generalize our discussion to the degree possible. After discussion of convective transfer at zero interfacial velocities we consider the complications introduced by chemical reactions and high net mass transfer rates.

We first consider film models of heat and mass transfer and concentrate our attention on turbulent transport in duct flows. In this discussion we compare available expressions for the turbulent transport properties and show that the best of these yield simple asymptotic correlations similar to the Chilton-Colburn relation for the Reynolds and Schmidt (or Prandtl) number ranges of most interest. Since adequate empirical correlations already exist for long ducts this discussion is most useful as a preparation for analysis of transfer in short ducts and mass transfer accompanied by chemical reaction.

We next consider forced-convection transport through laminar boundary layers and use as our prototypes penetration into a stagnant liquid and dissolution of a sparingly soluble duct wall. These are then generalized using the techniques pioneered by Acrivos and Stewart to systems of arbitrary geometry as suggested in Fig. 1. The key results of these analyses are:

\[ n_x = \frac{(Rc)^{1/3}}{\sqrt{\left[ \frac{2}{1} \right]}} \left( \frac{h_x h_r h_z}{\sqrt{h_x h_r h_z}} \right) \]  

\[ \text{(High } \Lambda; \text{ no slip)} \]

\[ (1) \]

Here \( h_x, h_r, h_z \) = scale factors for the locally orthogonal co-ordinates of Fig. 1.
\( \gamma_z \) = the dimensionless shear rate at the system boundary.
\( u_* = \text{dimensionless tangential velocity component at the interface.} \)

\( \lambda = \text{Schmidt or Prandtl number.} \)

Equation 2 is essentially that given by Stewart in his boundary-layer analysis of heat and mass transfer about three-dimensional solid bodies at high Sc or Pr. Equation 3 is a straightforward generalization of Acrivos’ development for two-dimensional and axisymmetric bodies at very low Sc or Pr. It is, however, actually most useful for describing steady transfer about drops and bub-
bles at very high Schmidt number. It is thus a special case of the surface-stretch modification of the penetration model discussed below.

After introduction of these rather general results the behavior of several real systems is discussed briefly to demonstrate both their utility and limitations.

We follow this discussion with introduction to free-convection transport and the challenging problems of transfer accompanied by chemical reaction and high net mass-transfer rates. In these latter discussions we place particular emphasis on the development of geometry-insensitive correlations.

B. Intraphase Transport in Systems with Mobile Interfaces

This section is devoted largely to extension of the penetration model to systems with stretching and shrinking interfaces. We follow here the approach of Angelo, Lightfoot, and Howard as refined by Stewart, Angelo, and Lightfoot. In doing this we make use of a similarity transformation first suggested by Ilkovic in 1934 and since independently re-introduced many times by other workers including Acrivos, Lochiel and Calderbank, and Scriven and Pigford.

We are able to show as a result of our analysis that the mass-transfer behavior of an extremely wide variety of fluid-fluid systems is described by the simple equation

\[ \overline{Nu} = \left[ \frac{1}{\kappa} \right] \left[ \frac{\left( \frac{\rho A}{\nu} \right)^{1/2}}{s(t)} \right] \]

where \( \overline{Nu} \) is the temporal mean Nusselt number for a surface element based on its area \( s_0 \) at an arbitrary reference time, and \( s(t) \) is the area as a function of the dimensionless time \( t^* \). The symbol \( A \) is used for Schmidt or Prandtl number. The term in braces in Eq. 4 is simply the penetration-theory result for a non-deformable surface element, and the correction factor \( \kappa \) is just the temporal root-mean-square value of \( s/s_0 \). Equation 4 is useful for drops and bubbles, rippling films, laminar jets, and many other important systems. Some of the most important of these are discussed in detail.

C. Interphase Transport

This discussion is devoted largely to a critical review of the two-film theory of Whitman and of Marangoni effects.

Surprisingly relatively few vigorous treatments of interphase transport are available, and it is still common practice to estimate overall coefficients by addition of separately calculated interphase resistances. We review the errors inherent in this approach and show that improper area averaging of local coefficients can be a particularly important source of error. In this discussion we follow much of the original treatment of King.

In fluid-fluid contactors variations in interfacial tension over the mass-transfer surface can have profound effects on both the shape of this surface and the flow conditions near it. These so-called Marangoni effects were first shown to be important in separations processes by Sherwood and Wei, and the first significant attempt to describe them quantitatively for process equipment was made by Sterning and Scriven by means of a linearized stability analysis. We consider in our course two simple analyses of Marangoni effects in falling films due to Ludviksson and Lightfoot and Wang, Ludviksson and Lightfoot. In addition to their simplicity these examples offer the advantage of direct application in simple process equipment. They can thus be used in our practical examples.

III. Approximate Descriptions of More Complex Systems

In this section we consider systems too complex for detailed rigorous analysis but which can be usefully analyzed in the light of the preceding sections. This is felt to be a very important part of the course since in practice engineers must usually stick their necks out and deal with a considerable amount of uncertainty. The purpose here is to show what sorts of approximations and simplifications are likely to be successful and to encourage the development of “engineering judgement”.

The specific examples we are presently using are:

1) Semi-quantitative descriptions of inertial rippling and Marangoni effects on mass and heat transfer in laminar falling films. We base these discussions on analyses and measurements performed in our own laboratory by Howard, Irani, Ludviksson, Massot, and Wang.

2) Prediction of re-aeration rates of streams using an extension of the analysis of Fortescue and Pearson.

3) Prediction of the performance of a sieve-tray liquid extractor from fluid-mechanic measurements, based on analyses and measurements of Angelo and Howard in our laboratory.
Union Carbide's research centers are in many ways like a university. In any one of them you'd meet a faculty with advanced degrees in practically every science. You'd see them scribbling complicated formulas on blackboards and working with complex scientific instruments.

You'd hear them discussing the uses of tremendous pressures, unearthly heat, intense cold—as well as problems in oceanography, outer space, atomic energy.

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They move on to new and exciting challenges created by today's advancing technology.
We have chosen these for familiarity and because they are (perhaps fortuitously) successful examples of the application of fundamentals introduced earlier in the course. We believe that unit operations should be taught this way when possible: from personal experience and in the light of available theory.

Plans for Future Development

It is obvious from this discussion that our course outline is too long, and each year we must slight some topics very badly to obtain meaningful coverage of others. We believe we must soon either expand to a one-year sequence or move much of Section I to a new course on the estimation of physical properties.

We particularly feel the need of more examples, both for consolidating the theory presented and for advertising new fields. We also feel that we are placing too little emphasis on inventiveness and ingenuity. This course is therefore far from satisfactory, even in its philosophy. We hope it will look very different five years from now.

BIBLIOGRAPHY


Kinetics of Chemical Processes
Michel Boudart,

To quote from the jacket of this volume "... Chemical kinetics, once the esoteric domain of the theorist, has become a vital tool in the design, operation and control of reactors ... ".

With the emergence over the past decade of chemical reaction engineering as an active and vital area in both teaching and research, the need for a book such as that Professor Boudart has provided us with here has become almost painful. To be sure, chemical engineering kinetics (whatever that is) is said to be the topic treated in a number of available texts. Kinetics, however, generally seems to bow out of the picture after quick tours through phenomenological rate forms, chain reactions and the steadystate approximation, numerous integrated rate equations and the inevitable Langmuir-Hinshelwood discussion. One is left in these texts with a substantial involvement in reactor analysis and design, which is certainly worthwhile, but kinetics then appear only as something taken for granted. Those who have attempted teaching reaction kinetics as distinct from reactor analysis or reaction engineering, know that the assembly of material for such a course at any level other than the trivial is a tiresome task of searching through a number (in my own case, six) of texts and monographs in the chemical and chemical engineering literature. No longer! In this admirable introductory text, Professor Boudart has put all the information together for us, clearly and concisely, while still leaving lots of latitude for us all to incorporate our own variations.

The approach of the book is straightforwardly put in the Preface: to develop the single chapter on kinetics in a physical chemistry text into a whole course, giving the essence of theory and experiment without indulging in extreme chemical detail. The contents include introductory material on rate functions and reactor types, theory of chemical kinetics of elementary steps, steady state treatments for various systems, chain reaction sequences, the concept of rate determining steps and stoichiometric numbers, irreducible (i.e., those arising from the reaction process itself) transport effects on kinetics, and correlation methods for both homogeneous and heterogeneous reactions. There are a number of points which demonstrate how well structured and carefully written this text is. For example, transition state theory is developed via the thermodynamic formulation, which very clearly distinguishes between energy and entropy contributions to reaction rates. The development given for reactions proceeding via elementary steps involving active centers — chain and catalytic sequences — provides a useful generalization for a large portion of kinetics, and the chapters on correlations in homogeneous and heterogeneous reaction kinetics provide a nice amalgam of information from sources which are diverse and perhaps not the most familiar. There are quite a number of problems included, and they are generally excellent. In short, this is a book which every chemical engineer should have in his library.

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OPTIMAL CONTROL OF REACTION SYSTEMS

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In this article we shall briefly outline some of the major topics covered in a graduate course in Optimal Control of Reaction Systems at Princeton. This course was originally started in 1955 as a full year of Numerical Analysis and has gradually evolved into its present form. This was achieved by the inclusion in 1959 of selected items (3 and 6 in Table II below) and the subsequent addition of more and more material until the present coverage resulted.

**TABLE I—TEXTS RECOMMENDED FOR COURSE IN OPTIMAL CONTROL OF REACTION SYSTEMS**


Table I lists a number of recommended texts which are used throughout the year and Table II gives some details on the explicit topics covered in the course. The main text references are I-2 and I-4, but all those shown in Table I are consulted at various points. Recent references have been included in Table II so that the reader or student has a convenient starting point for published material.

The course is devoted to the mathematical and numerical-computational aspects of the state-space or time-domain approach as distinguished from the frequency or transform domain. In general it covers deterministic problems although some stochastic control and the effects of noise are briefly treated near the end of the course. Extensive numerical and computer problems are given as exercises to allow the students to try their hand at applying the theory. As an example, the optimal control of a series of CSTR will be discussed in class and the same problem but with control delay will be given to the students to solve by a variety of algorithms. However, emphasis on complex physical reactions systems for complexity sake is kept to a minimum.

To give some perspective to the course objectives we present Figure 1 which is taken from an article of Kalman, Lapidus and Shapiro published in 1959 in the *Instrn. Chem. Engrs. Journal*. Here we show an on-line adaptive (learning) computer connected directly to a process or system. Within the computer there are three main programs designated A, B and C. The function of program A is to carry out the optimal control of
TABLE II—COURSE OUTLINE FOR OPTIMAL CONTROL OF REACTION SYSTEMS


7. Minimum Time Problem. Solution via Minimum Principle, concept of switching times, bang-bang control and singular control. Connection to linear and nonlinear programming. Refs.: Lesser, AIChE Jrn. 12, 143 (1966); Flynn, AIChE Jrn. 15, 308 (1969); I-2, I-3 and I-4 of Table I.


* Depending on the background of the students.

for iteratively solving the full nonlinear control problem. First (gradient) and second variation methods including quasilinearization, neighborhood extremals, and the use of the linear-quadratic procedure. Constraints and penalty functions. Open and closed-loop solutions. Refs.: I-2 and I-4 of Table I.


14. Filtering, Parameter Estimation and Identification. Linear and nonlinear systems determination of parameters, black box representation and computational questions. Refs.: Bard, Cat. Reviews 2, 67 (1968); Harris, AIChE Jrn. 13, 281 (1967); Peterson, Chem. Eng. Sci. 21, 665 (1966); I-6 of Table I.

* If enough time is available.

![Figure 1. A Possible Adaptive Digital Control System.](image-url)
The course is devoted to the mathematical and numerical-computational aspects of the state-space or time domain approach as distinguished from the frequency domain.

INTRODUCTORY MATERIAL

Because of the wide background of students who take this course it is necessary to first present certain introductory topics which are then used throughout the year. These include the complete vector-matrix notation and its uses such as evaluating the transition matrix and the pseudo-inverse, the numerical solution of ordinary and partial differential equations, the fundamental properties of convergence algorithms and some basic material on functional analysis. The solution of equations and the numerical stability of these solutions is necessary because they are an integral portion of all control algorithms and must be done correctly. Further, convergence algorithms are used throughout the entire course to actually obtain the optimal control.

In addition to these numerical concepts it may be necessary to present some preliminary details on the necessary and sufficient conditions for an unconstrained minimum of a multivariable function, the influence and effects of constraints and the use of Lagrange multipliers and penalty functions to handle constraints. These items, which can be developed for a simple two-variable function, can be carried over directly to the most complicated control problem. As such the concepts are absolutely necessary throughout the course.

TABLE III DEFINITION OF OPTIMAL DETERMINISTIC CONTROL PROBLEM

<table>
<thead>
<tr>
<th>1. General Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>Given:</td>
</tr>
<tr>
<td>2.</td>
</tr>
<tr>
<td>Control and State Constraints</td>
</tr>
<tr>
<td>4. Final Time Conditions (t_f)</td>
</tr>
<tr>
<td>5. I = g(x(t_0),t_0) + \int_{t_0}^{t_f} [x'(q) + u(t)du] Scalar Index</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2. Linear-Quadratic Form.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. x(t) = Ax + Bu</td>
</tr>
<tr>
<td>2. x, u are same</td>
</tr>
<tr>
<td>5. I = x(t_0)'Sx(t_0) + \int_{t_0}^{t_f} [x'(q) + u(t)du] Quadratic Index</td>
</tr>
</tbody>
</table>

Find u(t), t_0 \leq t \leq t_f, such that I is minimized subject to constraints of 1-5.

MAIN TOPICS

With these preliminaries in hand the next step in the course is to define the optimal control problem (see 1 of Table III) and to detail the minimum principle and the techniques of dynamic programming and invariant imbedding as general methods of solving the problem. Here it is very important to give numerical examples and to illustrate both the positive and negative features of these solution methods.

The linear-quadratic problem (see 2 in Table III) is then treated in detail using the minimum principle, dynamic programming and variational calculus. This is important because the techniques developed form the basis for all 2nd order algorithms for solving the full nonlinear control problem. Because of the availability of the ASP computer program (see 1-4) to numerically solve this linear-quadratic problem a number of different exercises are given to the students.

The minimum-time problem is then solved via the minimum principle and the connection to linear and nonlinear programming detailed. Computational considerations and the singular case are stressed. This area is interesting since it connects to programming methods and is applicable to the analysis of many reactor systems.

Next we discuss a wide variety of computational algorithms for solving the nonlinear control problem without and with constraints. These methods include the gradient (first variation) approach and the second variation including quasilinearization. Much of this analysis can be connected directly to the special linear-quadratic case already treated. In addition, consideration is given to a form of suboptimal control which is easily developed and yields a closed-loop type of approximate control. At the same time sensitivity considerations are employed to indicate the influence of parameter uncertainties and to generate iterative methods for the optimal control.

Since many reaction systems exhibit the features of stability and instability we then turn to a detailed discussion of the concepts of trajectory paths in the neighborhood (or global) of an equilibrium point. This leads directly into an analysis of multiple equilibrium points, non-uniqueness of solutions of nonlinear equations, limit cycles and Liapunov functions. In particular the Liapunov function approach is extended to distributed parameter systems and to provide convenient algorithms for minimum-time and suboptimal control.

The extension of many of the above ideas may
now be used advantageously to analyze the control of distributed parameter systems. Here we treat the control problem in its normal form or carry out a partial type of lumping (finite differencing) to convert the system to sets of ordinary differential equations. In both cases a variety of possible control algorithms following from the minimum principle and dynamic programming are developed.

Finally we consider the identification problem either in its full complexity where no apriori information about the reaction system is known or are developed.

Carrying out nonlinear least-square regression and fit the system data with generalized orthogonal polynomials. Questions such as the noise involved in the inputs and on the measurement are of importance.

AMUNDSON on Math (Cont’d from p. 177)

and some comments must be made and analogies are drawn with finite vector systems.

The object of such a course should be to present methods for new problems. If a problem has been solved once then the engineer should use it. But with a new problem there is no one to tell him when the problem is properly posed. Has the model been drawn so it makes mathematical sense and how does one test whether it does? Whether a solution fits certain physical and chemical requirements will be determined by comparison with experiment, but this comparison is meaningless if the model is not self-consistent.

There is frequent confusion in the minds of beginning graduate students on what is mathematics and what is not mathematics, and, if such a course serves no other function, this question should be answered for him. All of our problems as engineers are physically motivated and the translation of a problem into mathematical terms is not mathematics. The generation of the appropriate mathematical model is the job of a good engineer and whether conclusions drawn from the model agree with experiment is the test of how good an engineer he is. If the model does not agree with the experiments, one of two things may be at fault. Either the model was poorly drawn in that it does not describe the physical situation or the model is incomplete or inconsistent. Once the model is put to paper a mathematical problem must be solved. The engineer must somehow convince himself either by intuition or rigorous mathematical argument that the mathematical problem is properly posed. The old argument that the problem is a physical one and therefore possesses a unique solution is a useful argument but not infallible, since only nature solves physical problems and she is quite capable of giving a non-unique solution. The argument also betrays an unrealistic confidence in the engineer for it assumes that he has translated the physical problem into mathematical language exactly, a most unlikely event. This is really a very complicated problem, for in the course of the solution certain changes or approximations in the model, both physical and mathematical, are made and these should be examined in some detail to insure that the structure has not been destroyed.

In conclusion, such a graduate course should not only teach techniques but it should also give the student a feel for what he is doing and what is involved. It has been frequently asserted that we teach only mathematics and neglect engineering. On the contrary, we are trying to teach the student the proper place and function of mathematics, showing not only its strengths but also the pitfalls which may befal the unware and the uninstructed.

BIBLIOGRAPHY

Chemical thermodynamics started with J. Willard Gibbs nearly 100 years ago but its significant influence on chemists and chemical engineers in the United States, starting about 50 years ago, is due in large measure to the work of G. N. Lewis, who introduced fugacity and activity. For many years Lewis’ strong personality dominated the College of Chemistry at the University of California at Berkeley; he served as its dean from 1912 until shortly before his death in 1946. It is therefore not surprising that Berkeley’s College of Chemistry (which includes the Department of Chemical Engineering) has retained a tradition of strong interest in the application of thermodynamics to chemical problems.

While Lewis’ early work in thermodynamics was along classical lines, in his middle and later years he devoted much attention to relations between molecular physics and thermodynamic properties. Classical thermodynamics establishes broad relations between macroscopic equilibrium properties but, by itself, it cannot generate numerical values of these properties; further, it is limited in its ability to suggest useful techniques for interpreting and correlating them. For such purposes, we must call on the insights provided by statistical mechanics and molecular physics. Lewis’ efforts in this area were accompanied and continued by various collaborators, including W. F. Giauque (who won the Nobel prize for his low-temperature work) and later, Leo Brewer and K. S. Pitzer (now president of Stanford University). But, with respect to chemical engineering education and research in thermodynamics, the most important of Lewis’ collaborators was (and is) Joel H. Hildebrand, who at age 88 is still active in research on the properties of liquid solutions.

Hildebrand’s numerous publications have shown that when thermodynamics is coupled with simple (often semiempirical) molecular models, many practical phase-equilibrium problems can be solved with a minimum of effort, and what is more important, with a minimum of experimental data. It is this feature of Hildebrand’s work that has become the major influence on the course “Phase Equilibria” in the Chemical Engineering Department at Berkeley.

The course is normally taken by graduate students in their first quarter at Berkeley. It meets twice a week; each meeting is for one and a half hours. Prerequisites for the course are a one-year course in undergraduate physical chemistry and at least a one-quarter course in undergraduate chemical engineering thermodynamics; almost all entering graduate students satisfy these prerequisites. The two main purposes of the course are: (1) to give students the background needed to apply thermodynamics and molecular physics toward the solution of practical phase equilibrium problems as required in typical chemical engineering design practice, and (2) to provide an introduction to applied molecular science for tackling new problems on the frontier of modern chemical engineering. The student acquires some feeling for the physical (as opposed to the merely mathematical) significance of thermodynamic functions and some insight into the intermolecular forces which determine the magnitude of these
functions. He gains practice in reduction and interpretation of experimental data and in devising efficient and physically meaningful methods for data correlation. Most important, he achieves some perspective on what kind of experimental information he requires for a given problem and, lacking that information, he gains experience in quantitatively estimating desired phase equilibrium relations from a minimum of experimental data. Finally, he becomes acquainted with some of the literature on phase equilibrium thermodynamics and learns, often to his great surprise, that he must be critical of what he reads since this literature, unfortunately, is not free of errors.

The course is divided into ten somewhat arbitrary sections which are given in Table 1. These sections correspond to the ten chapters of a recent textbook* J. M. Prausnitz, “Molecular Thermodynamics of Fluid-Phase Equilibria,” Prentice-Hall, Inc., Englewood Cliffs, N. J., 1969.

Section two is devoted to classical thermodynamics of phase equilibrium. The third section deals with the activity; a worked-out simple example (Raoult’s law of corresponding states). A brief discussion is given of such “chemical” forces as hydrogen bonding and charge-transfer complex formation. Emphasis is given to qualitative and semiquantitative relations between intermolecular forces and macroscopic properties.

Section five begins with a critical discussion of the virial equation of state: its theoretical significance, its utility and limitations for calculating fugacity coefficients in gas mixtures. Attention is given to the exact relations between virial coefficients and intermolecular potential functions and to the composition dependence of virial coefficients. The “chemical” theory of gas imperfections is discussed. Semiempirical methods (e.g., the Redlich-Kwong equation) are presented for finding fugacity coefficients at high densities, and it is shown how these are used to calculate solubilities of liquids and solids in compressed gases.

Excess functions and their application to liquid mixtures are considered in section six. Various

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Table 1. Berkeley’s Course in Phase-Equilibrium Thermodynamics

1. The Phase Equilibrium Problem
2. Classical Thermodynamics of Phase Equilibria
3. Thermodynamic Properties from Volumetric Data
4. Intermolecular Forces
5. Fugacities in Gas Mixtures
6. Fugacities in Liquid Mixtures; Excess Functions
7. Fugacities in Liquid Mixtures: Theories of Solutions
8. Solubility of Gases in Liquids
9. Solubility of Solids in Liquids
10. High-Pressure Equilibria

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equations for representing activity coefficients (van Laar, Margules, Wilson, NRTL, etc.) are discussed. Consideration is given to multicomponent mixtures and to systems with partial miscibility. The significance and uses of the Gibbs-Duhem equation are given special attention.

Section seven is an introduction to the theory of liquid solutions. Brief attention is given to the lattice theory of simple mixtures and of polymer solutions; emphasis is placed on the theory of regular solutions, on applications of corresponding states theory, and on the "chemical" theory of associated and solvated solutions. All theories are regarded critically; advantages and disadvantages are pointed out.

Sections eight and nine are concerned with the solubilities of gases and solids in pure solvents and in solvent mixtures. Physical and chemical effects on solubility are pointed out and special attention is given to the importance of the standard-state fugacity of the solute.

The course ends with a brief discussion of the uses of thermodynamics to describe systems at high pressure. Special emphasis is given to the important role of the partial molar volume. Vapor-liquid, liquid-liquid and gas-gas equilibria are considered.

As outlined above, the course appears to contain a lot of material. However, experience has shown that well-prepared first-year graduate students can handle the course without difficulty provided their total course load is not large.

Typical first-year graduate students at Berkeley usually take only a total of two lecture courses plus one seminar course per quarter. Careful reading of the text (which was available in mimeographed form until its recent publication) is augmented with reading of "classical" original articles which are kept on reserve in the College of Chemistry library. Eight problem sets give the student practice in applying what he has learned to the solution of practical phase equilibrium problems. All problem sets are corrected by a teaching assistant and the more difficult problems are discussed in class.

The course provides a good partial foundation for subsequent graduate courses in separation operations, in process design and in medical engineering. For those students interested in doing research in molecular science and engineering it provides background and perspective for subsequent courses in statistical mechanics and in advanced chemistry, physics, and materials science.

The often-praised versatility of the chemical engineer, his ability to tackle a wide variety of new problems, is in large measure due to his knowledge of applied physical chemistry. Berkeley's course in phase equilibrium thermodynamics aims to contribute to that knowledge while at the same time providing the student with some of the skills for the practice of conventional chemical engineering.

LETTERS (Cont'd from p. 167.)

AN ADVENTURE IN TEACHING

Sir: During a recent conversation one of my graduate students described a course he was taking. The professor wrote everything down on the blackboard. He defined each symbol of every equation. Definitions were given of each technical word. Discussion was limited to students asking for clarification of the professor's handwriting. And then he added, "It wasn't like the Rate Processes course you taught last year". That had been an exciting learning experience for him. It had been the same for me.

I was teaching the second quarter of Rate Processes to first-year graduate students of varied backgrounds. In the first quarter we had covered the Momentum Transport section of "Transport Phenomena" by Bird, Stewart, and Lightfoot (BSL). This quarter I decided to teach Energy and Mass Transfer by the "row" approach. As the authors point out in the preface this alternate approach is suitable for graduate students. It emphasizes the type of transport and the analogies between the transport phenomena. Realistically it also eliminated the possibility that only a week or two at the end of the quarter would be left for Mass Transport.

The first topic covered was methods for predicting thermal conductivities and binary diffusivities. Since this touched on the area of my doctoral research, I added current literature methods to the text material and the students evaluated:

- Variation of thermal conductivity for sulfur dioxide, carbon tetrafluoride, and tungsten hexafluoride over the temperature range of 0 to 1000°C.
- Comparison of thermal conductivities of ammonia, carbon tetrafluoride, and hydrogen at three elevated pressures with experimental values.
- Variation of the binary diffusivities of tungsten hexafluoride and hydrogen fluoride over the temperature range of 0 to 1000°C.

Three lessons were learned from this exercise. First, beware of phase changes when computing transport properties (melting point of tungsten hexafluoride is 2°C and critical point is 178°C). Second, use of available sources of or estimation techniques for intermolecular force parameters. Finally, a feel for the accuracy of generalized correlations for transport properties.
Shell balances for simple energy and mass transfer problems (Chapters 9 and 17) came next. This was followed by the equations of change for nonisothermal systems and also the equations of change for multicomponent systems. The latter topic stirred everyone's interest. One of the reasons, I guess, was because it was so difficult. Another reason was that we had finally arrived at equations which encompassed all of the fluxes that would normally be encountered in any problem. In other words these equations presented the whole story.

Up to this point the course had been interesting but very conventional. All of us had learned some new ideas. But the real breakthrough was to come. Unscheduled. Unexpected. A real example of serendipity in teaching.

An AIChE meeting was scheduled for St. Louis in approximately the middle of the quarter. I was planning on attending and was trying to figure out what the students should do in my absence. Sounds familiar, doesn't it? What I hit upon was to assign each student a paper to review. Since mass transfer seemed to be the area of highest interest, most of the papers were in this area. (See list of papers assigned.) Some related to the students interests as I was aware of them. None were by BSL because this would have been unfair in the light of the review I requested. Here are the things I wanted them to include in a written review and also in a fifteen minute presentation before the class:

- Put the important equations and boundary conditions of the paper in BSL notation. Are these equations in BSL or what equations in BSL are they related to?
- What are the basic assumptions in the starting equations and do the authors clearly state them? What are the unstated assumptions?
- Prepare a clear diagram showing problem solved. Show concentration, velocity, or temperature profiles in diagrams.
- State the three most important contributions of the paper.
- Should BSL include results in revision of the textbook and why?

What a surprise I had in store when I returned from St. Louis! Fifteen minutes turned out to be woefully inadequate for any of the students to discuss their papers. I extended the time limit to an half hour. Even this proved inadequate. Discussion on some of the papers lasted as long as an hour after the formal presentation. This was exciting, I finally had to limit discussion so that all of the papers could be discussed within the quarter!

From this experience I gained new insight into what constitutes effective teaching. First, teaching was not my exclusive domain in the classroom. Students could teach one another and also they could teach me. In other words, teaching can be listening. How foreign that concept is among professors I've known. How foreign it was to me. Also, how threatening! Prior to this I felt that everything depended on my performance in the classroom. If I presented a well-prepared lecture, including good examples to illustrate the material, then students could learn. But I always had a gnawing feeling that there must be other ways and probably better ways of teaching. One of these is embodied in the concept of teaching is listening.

Secondly, students can evaluate themselves. Each student graded (anonymously) each talk. The average was their letter grade for the presentation. I was so awestruck by the talks I probably would have given them all A's. The students were more objective and gave an equal number of A's and B's. Grades which I gave on the written reports agreed very closely with those of the students.

Relevancy is an overworked word in today's student vocabulary. It denotes that classroom learning has meaning in or can be applied to the real world and its problems. Unexpectedly, this teaching adventure touched on something that was relevant to the students. We had all progressed to a common ground of understanding transport phenomena. With this each student attacked a paper in the literature and found that what we had learned applied to that paper. And each student could do his own thing within the guidelines laid down. Further each student had the opportunity to experience that greatest satisfaction of teaching; namely, to teach is to learn. Frankly, we need to share this sense of fulfillment with our students more often. In a future paper I'll tell how I did this with undergraduate students.

In closing let me share one of the other things my graduate student told me. He said that one of the students finished his report while I was away. He then cornered each of his classmates individually and went over his report with them soliciting questions and comments. As I recall his lecture was the best. More importantly, I know he had experienced an adventure in teaching.

PAPERS ASSIGNED


Charles E. Hamrim, Jr.
University of Kentucky

(Continued on page 233.)
Shell is a pair of sneakers—made from our thermoplastic rubber.

Shell is a milk container—we were a pioneer in the all-plastic ones.

Shell is a clear, clean country stream—aided by our non-polluting detergent materials.

Shell is a space capsule control—energized by Shell's hydrazine catalyst.

Shell is food on the table—made more plentiful by Shell's fertilizers.

Shell is mileage gasoline—developed through Shell research.

Shell is a good place for Chemical Engineers to build a career.

Shell is an integrated research, engineering, exploration and production, manufacturing, transportation, marketing organization with diverse technical operations and business activities throughout the United States. Chemical Engineers are vital to the Company, applying their knowledge to recovering oil from the ground; designing and operating oil, chemical and natural gas processing plants; developing new marketing and product application methods; and carrying out research and development to support all of these. Information about openings throughout Shell may be obtained by signing at the Placement Office for an interview with our representative, or by writing to Recruitment Manager, The Shell Companies, Department C, Box 2099, Houston, Texas 77001. Shell is an equal opportunity employer.
Venture: Purify water with the fiber that made men whistle.

Nylon. Reverse osmosis. A fiber that started making girls' legs more beautiful some 30 years ago. And a process that's been around a lot longer.

But when Du Pont scientists and engineers look at them in a new way, they combine into an idea that can change the world.

Reverse osmosis is a purification process that requires no phase change. It's potentially the cheapest way to desalinate water.

Du Pont's innovation? Hollow, semipermeable nylon fibers much finer than human hair. Symmetrical, with an outer diameter of .002 inch and a wall thickness of .0005 inch, with an accuracy of manufacture maintained at close to 100%. Twenty-five to 30 million of them encased in a precisely engineered unit 14 inches in diameter by 7 feet long.

The result: a semipermeable surface area of about 85,000 square feet—the size of a 2-acre lot—and up to 10,000 gallons of desalted water per day.

So far "Permasep® permeators have been used experimentally to purify brackish and polluted water, and in various industrial separations. But the potential to desalt seawater, too, is there.

So Du Pont scientists and engineers are even now working toward improved fibers, units and plant designs that should make it possible to get fresh water from salt at a price that any town or nation can afford.

Innovation—applying the known to discover the unknown, inventing new materials and putting them to work, using research and engineering to create the ideas and products of the future—this is the venture Du Pont people are now engaged in.
THE GRADUATE STUDENT VERSUS THERMODYNAMICS

JOSEPH J. MARTIN
University of Michigan,
Ann Arbor, Mich.

Thermodynamics has the reputation, enviable or not, of being a worthy adversary for those who dare to engage it in battle. For most young proteges there are many rounds of rough in-fighting before mastery of the subject can be claimed. This is not because of its sheer logic, for mathematics is undoubtedly the queen of the sciences in this respect, and mathematics does not seem to offer the same degree of difficulty. Rather, it is more probably due to the extreme range of application of thermodynamic principles. Although Webster says that “thermodynamics is the science which treats of the mechanical action or relations of heat,” it is much more appropriate to say that thermodynamics is the science of energy and entropy which is involved in every equilibrium state of matter and every process or change that occurs in the real ponderable universe.

As an undergraduate the young protege is exposed to the so-called “laws of thermodynamics,” of which there are just four as follows:

Zeroth. If a thermometer shows the same reading when in separate contact with two objects, no change occurs when the two objects are touched to each other.

First. Energy and mass are simultaneously conserved (accountable) in all processes and individually conserved in most cases.

Second. Actual processes occur in one direction and the initial conditions will never be restored without the aid of some outside agent.

Third. The entropy of a pure substance in perfect crystalline form vanishes at the absolute zero of temperature.

The zeroth and second laws are quite acceptable to the undergraduate because he has had some experience with thermometers and because he has learned the irreversible ways of mother nature from the time of his first broken dish or balloon to the time he has burned the last drop of gasoline in his car many miles from a service station. The first law is palatable because energy and mass balances are mathematically neat, but the protege is often shaky on the general concept of energy. He finds it difficult to explain the nature of internal energy or to tell just where energy is stored when a weight is lifted in a gravitational field. The third law makes sense to him only insofar as he understands the abstract quantity, entropy, and the absolute temperature scale.

It is generally not the laws of thermodynamics which present the greatest difficulty to the novice in the field, but the hundreds of equations which have been developed to permit quantification of the elementary principles embodied in the laws themselves. Fortunately, however, there are just four basic equations from which all others are derived by suitable mathematical manipulation. These four questions do not have a one to one correspondence with the four laws, but collectively they incorporate the first three laws within their structures. The four equations are:

The Fundamental Property Relation of Matter
(Gibbs Equation),

\[ dU = TdS - PdV + \sum_{i=1}^{N} \mu_i dm_i \]  

The Energy Balance on a System,**

\[ d(U+\sum_{j}^{\infty} \frac{m_j^2}{2} + mgz)_{sys} = \delta Q - \delta W + \sum_{j=1}^{K} (\frac{\delta u_j}{2} + g\delta z_j) dm_j \]  

*See the Nomenclature at the end for the definition of symbols.

**A system is any portion of the universe chosen for analysis, and may have many distinct parts.
The Entropy Balance on a System

\[ \mathrm{d}S_{\text{sys}} = \sum_{i=1}^{n} \left( \frac{\partial Q}{\partial T} \right)_i \mathrm{d}T + \sum_{j=1}^{K} \left( \frac{\partial L}{\partial T} \right)_j \mathrm{d}T + \sum_{j=1}^{L} \frac{\partial L}{\partial T} \mathrm{d}T \]

The Mass Balance on a System

\[ \mathrm{d}m_{\text{sys}} = \sum_{j=1}^{K} \mathrm{d}m_j \]

Although it may appear to be an oversimplification of the subject, there is little question but what complete understanding of the four basic equations amounts to a mastery of classical thermodynamics. The equations are, therefore, introduced to the protege at an early stage, even though it is quite unlikely that in a single course he will perceive all of their underlying implications. The graduate student who is exposed to one or more succeeding courses will gradually gain a more complete understanding of the extreme power and utility of the four equations to describe the thermodynamic character of all processes and all equilibrium states of matter.

The first of the basic equations is probably the most important and the protege learns that a uniform mass of matter has the extensive thermodynamic properties, internal energy, entropy, volume, and mass of each component, and the intensive properties (potentials), temperature, pressure, and chemical potential of each component. The point to be emphasized is that these properties are not completely independent, but are interlocked through Eqn. (1). Any change in the condition or state of matter will cause changes in the thermodynamic properties, but the changes cannot occur indiscriminately; they must occur in accordance with this differential equation. In the deduction of the several terms in the equation, the inclusion of entropy is paramount. It is done in one approach by saying that for a simple heat transfer to the exclusion of any other effect the change of entropy is the change of internal energy divided by temperature, or \( \frac{\mathrm{d}S}{\mathrm{d}T} = \frac{\Delta U}{T} \). This makes \( S \) extensive in the same manner as \( U \). The desirability of defining entropy this way is best understood by noting that, for example, when a hot object is touched to a cold object in isolated conditions, the energy balance shows nothing is lost since \( \Delta U_{\text{both}} = \Delta U_H + \Delta U_C = 0 \). Yet experience and intuition tell us that something has changed and the ability to do work has been lost. Calculating \( \frac{\Delta U}{T} \) (i.e., entropy change) for both objects shows \( \Delta S_{\text{both}} = \Delta U_{\text{both}} + \Delta U_{\text{C}} = \Delta S_{\text{both}} > 0 \) because \( \Delta U_H = -\Delta U_C \) and \( T_H > T_C \). The change in entropy, \( \Delta S \), provides a quantitative measure of the irreversibility of the heat transfer. Its relation to the work lost is given by Eqn. (3).

The unusual mathematical character of Eqn. (1) being an exact differential and homogeneous of the first degree permits it to be integrated to

\[ U = TS - PV + \sum_{i=1}^{N} \mu_i m_i \]

and then differentiated to

\[ 0 = SAT - VdP + \sum_{i=1}^{N} \mu_i dU_i \]

which is the Gibbs-Duhem equation that is worthy of extended contemplation by the protege. Because \( U, TS, \) and \( PV \) often occur together as in (5), it is convenient to define \( H = U + PV, A = U - TS, \) and \( G = H - TS, \) but it is obvious that although very handy and efficient, \( H, A, \) and \( G \) are not fundamental properties. By rules of partial differentiation and the definition of heat capacity as

\[ C_X = T(dS/dT)_X \]

it is possible to put Eqn. (1) in such seemingly unrelated forms as

\[ dS = C_P dT - (dV/dT)_P dP \]

and many others. In fact, the bulk of thermodynamics involves the application of Eqn. (1) in different ways to a wide variety of situations involving ponderable matter.

In the second basic equation, the energy balance, the protege notes how heat and work are introduced with arbitrary signs, and the reason for distinguishing flows of energy to the system by "\( q \)" and changes of energy within the system by "\( d \". The most common applications of the equation are in three integrated forms:

**Closed System,**

\[ Q - \Delta W = \Delta U_{\text{sys}} \]

**Steady-Flow System,**

\[ Q - W = \Delta H + \Delta (u^2/2) + g\Delta z \]
Single-Flow System,

\[ \int_{\text{sys}}^{} Q + W = \left[ (\text{U}_m) - (\text{U}_m) \right] \]

(12)

Of course, the energy balance may take many other forms by proper specialization of Eqn. (2) for particular cases.

The third basic equation, the entropy balance, is useful for calculation of the work lost in real irreversible processes and for analysis of idealized reversible processes. The protege is quite aware that a tank of compressed air can do useful work by connecting it to an expansion engine and that such work can be forever lost by allowing the air to leak out instead of flowing through the engine. He is equally aware that an outside agent must do work on the air that leaked out in order to get it back into the tank. He will readily appreciate that this work of restoration under certain ideal conditions is the work lost during the irreversible leaking process.

For many applications the entropy balance is applied to closed systems as a simple integral,

\[ \int_{\text{sys}}^{} TdS = Q + LW \]

(13)

In this form it is seen that for a non-flow reversible process (no lost work) the heat transfer equals the \( \int TdS \). If in addition there is no heat transfer (adiabatic as well as reversible), the \( \int TdS \) vanishes and the process is isentropic. When Eqn. (3) is applied to a reversible heat engine operating in a steady state (no lost work, no change of entropy of the system—the engine, no mass flow—only heat and work flow),

\[ \Sigma_i(\delta Q_i/T_i) = 0 = \delta Q_{\text{h}}/T_{\text{h}} + \delta Q_{\text{f}}/T_{\text{f}} \]

This may be combined with the energy balance, \( \delta Q_{\text{h}} + \delta Q_{\text{f}} - 6W_x = 0 \), to give

\[ 6W_x = \delta Q_{\text{h}} \left( \frac{T_{\text{h}}}{T_{\text{h}}} \right) = \delta Q_{\text{f}} \left( \frac{T_{\text{f}}}{T_{\text{f}}} \right) \]

(14)

which is the Carnot relation that is utilized in the analysis of heat engines and heat transfer processes. Here it is desirable that the protege become familiar with heat engine cycles that are used in steam plants, gas turbines, and reciprocating internal combustion engines. The concept of available energy should be included also.

The energy and entropy balances may be combined in another manner by eliminating \( Q \) between Eqn. (11) and Eqn. (13) applied to a unit mass of flowing material, and utilizing the definition of

\[ G = H - TS \text{ or } \Delta G = \Delta(TS) - \int \text{f}dT, \text{ so that } \]

\[ -LM - W = \Delta G + \int \text{f}dT + \Delta(u^2/2) + g\Delta z \]

(15)

By using the property relation, \( \Delta G = \int VdP - LdS \), which is just a case of Eqn. (1) for the unit mass, another energy-entropy balance form is

\[ -LM - W = f_{\text{f}}dP + \Delta(u^2/2) + g\Delta z \]

(16)

which is Bernoulli’s equation. This equation has proven extremely useful in the treatment of a wide variety of fluid flow problems, particularly those in which there is friction lost work. For a reversible process no work is lost and (16) becomes

\[ -LM - W = f_{\text{f}}dP + \Delta(u^2/2) + g\Delta z \]

(17)

while (15) becomes

\[ -LM - W = f_{\text{f}}dP + \Delta(u^2/2) + g\Delta z \]

(18)

The last two equations find applications in the flow work concept of equilibrium between two states. By this concept if two states are in equilibrium, no work can be obtained from a transfer or flow of mass between them. Direct use of the equations furnishes an analysis of non-isothermal equilibrium, which is equilibrium superimposed on a steady-state irreversible heat transfer. Most applications, however, are to isothermal equilibrium so that Eqn. (18) is written

\[ 0 = \delta Q_{\text{h}} + \Delta(u^2/2) + g\Delta z = \delta Q_{\text{h}} + m\Delta(u^2/2) + mg\Delta z \]

(19)

If component \( A \) in a mixture is free to move between two states in equilibrium, (19) may be written

\[ 0 = \delta A_{\text{h}} + \Delta(u^2/2) + g\Delta z \]

(20)

This is the key equation of phase equilibrium and to understand its implications, it is necessary to become familiar with partial extensive properties as derivatives of any extensive property with respect to mass of component \( A \) at constant \( T, P \), and masses of all other components. For free energy, as an example, \( G_A = (dG/ dm_A)_T, P \) \( m_B \)

\[ G = m_A G_A + m_B G_B + \ldots \]

(21)

This may be compared with the property relation (1) to show that \( G_A = \mu_A \)

(22)

Further comparison with (5) shows that

\[ G = m_A G_A + m_B G_B + \ldots \]

(23)

When one has gained confidence that a partial property of a component of a mixture is essentially the same as the unit mass property of a pure substance, he sees how most of the equations for pure and mixture components are interchangeable. For example, by proper manipulation of the fundamental property relation (1) he can get both

\[ \frac{d(G/T)}{dT} = \frac{-H}{T^2} \]

(24)
which are Gibbs-Helmholtz equations.

The protege’s level of sophistication in thermodynamics is advancing rapidly if he fully comprehends the definition and use of fugacity and activity through the equations,

\[
d\bar{G}_A = RT d\ln \bar{f}_A \quad \text{where} \quad \bar{f}_A = p_A \quad \text{as} \quad p = 0
\]  

and

\[
d\bar{G}_A = d\bar{G}^O_A + RT \ln \frac{\bar{f}_A}{\bar{f}^O_A} = d\bar{G}^O_A + RT \ln \bar{a}_A
\]  

Here integration has been conducted isothermally from a chosen standard state * to any state. When Eqns. (23) and (27) are applied to a reaction, \(aA + bB \rightarrow cC + dD\), at a given temperature and no kinetic or potential effects, Eqn. (18) yields

\[
-W = \Delta G^O + RT \ln \frac{\bar{f}_A}{\bar{f}^O_A} = \Delta G^O + RT \ln \bar{a}_A
\]  

At equilibrium where \(W = 0\), this becomes

\[
\Delta G^O = -RT \ln \bar{a}_A \quad \text{(K} = J_{\text{Equilibrium}}\text{)}
\]  

Then substituting Eqns. (8) and (25) into the temperature derivative of (29), and integrating between two temperatures, the following equation for situations without appreciable latent heat effects can be obtained by a person who has a good grasp of the subject,

\[
\ln \frac{\bar{f}_A}{\bar{f}^O_A} = \frac{\Delta H^O}{R} \left( \frac{1}{T_2} - \frac{1}{T_1} \right) + \int_{T_1}^{T_2} \frac{C_{\text{prod}} - C_{\text{react}}}{RT^2} dT
\]  

At the same time this move is made, it is desirable that the protege learn how to use certain tabular values of thermodynamic functions so that he can evaluate

\[
\left( \frac{\Delta G^O}{T} \right) - \ln \bar{a}_A = \ln \bar{a}_A - T \left( \frac{\Delta C_p^0 - \Delta C_p^f}{R} \right) _{\text{prod}} - \int T \left( \frac{\Delta C_p^0 - \Delta C_p^f}{R} \right) _{\text{react}} dT
\]

The protege’s knowledge should extend to electrochemical reactions, so that he understands the relations involving electrical work and voltage, such as

\[
W = N \tilde{\Delta} E
\]

\[
\frac{d(\tilde{\Delta} E^O/T)}{dT} = \frac{\Delta H^O}{N\tilde{\Delta} T}
\]

\[
N\tilde{\Delta} E^O = RT \ln K_a
\]

The entropy balance is useful for calculations of the work lost in real irreversible processes and for analysis of idealized reversible processes.

\[
N\tilde{\Delta} E = N\tilde{\Delta} E^O - RT \ln J_a
\]

by defining the activity coefficient, \(\gamma = \bar{f}_i / \bar{f}^O_i\)., it is desirable to be able to proceed from Eqn. (6) to get

\[
x_A d\ln \gamma_A + x_B d\ln \gamma_B = 0
\]

\[
\int_0^1 \ln \frac{\gamma_A}{\gamma_B} dX_A = 0
\]

and

\[
\ln \gamma_A = \int_{X_A=1}^{X_A=0} \frac{\gamma_B}{X_B} d\ln \gamma_B
\]

Rewriting Eqn. (20), for simple phase equilibria,

\[
\bar{G}^a_A = \bar{G}^b_A
\]  

and utilizing (27), the extremely useful relation,

\[
\bar{G}^a_A = \bar{G}^b_A
\]

is obtained. From the definition of the activity coefficient the equation for liquid-vapor-equilibrium is often shown as

\[
(\gamma_A x_A f_A^O)^{\text{liq}} = (\gamma_A x_A f_A^O)^{\text{vapor}}
\]

For ideal solutions the protege learns that if he appreciates the significance of assuming \(\gamma_A = x_A\), he can derive

\[
\bar{G}^a_A = \gamma_A f_A^O
\]

\[
\Delta G_{\text{ideal mix}} = RT (n_A \ln n_A + n_B \ln n_B)
\]

Equally useful relations for enthalpy and entropy may be obtained.

For non-ideal solutions it is desirable to see how

\[
\Delta G_{\text{ex}} = \Delta G_{\text{mix}} - \Delta G_{\text{ideal mix}} = RT (n_A \ln n_A + n_B \ln n_B)
\]  

and for regular solutions how

\[
\Delta G_{\text{reg}} = x_A (1 - x_A) a + RT (x_A \ln n_A + x_B \ln n_B)
\]

The empirical and semi-theoretical techniques for obtaining activity coefficients or required PVT behavior or an empirical constant such as \(a\) must be introduced at each step in which real problems are considered. Calculation of actual situations leads to the application, employment, and even development of correlations of the properties of matter. It behooves the protege to master many of these in the course of mastering the fundamentals of thermodynamics.

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Nothing has been said about the fourth basic equation since it is generally used directly as is. Clearly, however, if an application is contemplated to an extremely high energy process, such as a nuclear reaction or high velocity particles, the Einstein relation, \( E = mc^2 \), must be employed. In such a case the individual mass and energy balances must be modified to allow for the equivalence of mass and energy.

### Numerical

<table>
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<tr>
<th>T</th>
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<tbody>
<tr>
<td>u</td>
<td>Internal Energy</td>
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<td>v</td>
<td>Velocity</td>
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<td>w</td>
<td>Work</td>
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<td>y</td>
<td>Mole fraction</td>
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<td>z</td>
<td>Height above datum plane</td>
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<td>a</td>
<td>Activity coefficient</td>
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<td>Activity coefficient</td>
</tr>
<tr>
<td>e</td>
<td>Activity coefficient</td>
</tr>
</tbody>
</table>

### Solution

**Barometric pressure at top:** Consider a stagnant column of air outside the stack. Since it is at equilibrium (no flow) with no kinetic effects, Eqn. (17) applies as

\[
f_{\text{top}} = \frac{P_{\text{top}}}{P_{\text{base}}} = \frac{\text{gaz}}{\text{base}}
\]

**Solution:** For barometric pressure at top consider a stagnant column of air outside the stack. Since it is at equilibrium (no flow) with no kinetic effects, Eqn. (17) applies as

\[
0 = f_{270} + \frac{\text{gaz}}{\text{base}} = \int_{\text{base}}^{\text{top}} \frac{dP}{P} + \text{gaz}
\]

Several example problems and solutions are presented in the following section.

### ChE problems for teachers

The following problems with solutions were submitted by Professor J. J. Martin.

**No. 1.** One hundred million standard cubic feet (60°F, 1 atm) per day of radioactive waste gas at 100°F must be released at a height of 400 ft, above the ground to avoid contamination of the surrounding area. A circular stack of uniform diameter is to be used. A draft at the base of the stack of 1 in. of water will be required (pressure inside stack base is 1 in. H₂O less than barometric pressure). The barometric pressure at the base of the stack is 740 mm Hg and the ambient temperature 60°F. The gas has a molecular weight of 216 and may be considered an ideal gas. What diameter will be required?

**Solution:** Apply the energy balance Eqn. (2) to the whole device. Assuming negligible kinetic and potential effects, and

\[
\delta Q = \delta W = \delta E_{\text{sys}} = 0
\]

Let \( \delta m_j = 1.35 \), \( \delta m_c = 1.0 \), \( \delta m_b = 2.35 \)

Taking the reference state of air at 80°F and 20 psia, and assuming ideal gas behavior with \( C_p = 7.0 \text{ Btu/lb mole}' \),

\[
H_1 = 0, \quad H_2 = 7(280-80) = 1400, \quad H_3 = 7(190-80) = 850
\]

Substituting in the energy balance

\[
0 = (1400)(1.35) + (1850)(1) = 0 \quad \text{So energy balance OK.}
\]

Apply the entropy balance as

\[
\text{d}s = \delta S_{\text{sys}} = \int \frac{dQ}{T} - \delta(U) = 0 \quad \text{for steady state}
\]

or

\[
\frac{\text{d}s}{\text{d}T} = \frac{(\text{gaz})_1 - \text{gaz}_h}{(\text{gaz})_h - \text{gaz}_c}
\]
Integrating Eqn. (8), $\Delta G = C_p \ln \left[ -\frac{\Delta H}{\Delta S} \right]$

Using this to calculate entropies with respect to the reference state,

$S_1 = 0, S_n = 7 \ln \left( \frac{740}{549} \right) - 1.99 \ln \left( \frac{14.3}{29} \right) = 2.815$ and $S_2 = 7 \ln \left( \frac{270}{549} \right) - 1.99 \ln \left( \frac{14.3}{29} \right) = -4.24$

Putting these into the entropy balance gives

$\ln \left( \frac{\Delta S}{\Delta H} \right) = 0 - (2.815) (1.35) - (-1) (-4.24) = 0.44$

or $\Delta S = -0.44 \; T_0$

$T_0$ is the temperature at which heat may be rejected to the surroundings, so

$\Delta S = (-0.44) (540) = -237$

This, however, is impossible because the minimum value of lost work in a perfect process (reversible) is zero. There is no such thing as negative lost work (gained work). Thus, the data from the experiment must be in error. In other words, do not invest in this device if successful exploitation is dependent upon the above data.

No. 3. A mixture consisting of 33-1/3% by volume methane and 66-2/3% oxygen at 25 °C and 1 atmospheres total pressure is fed to a combustion chamber where the methane is burned completely at 1800 °C. The combustion products are then cooled and expanded at constant composition to 25 °C and 1 atmosphere pressure. Assume ideal gases and surroundings at 25 °C and no condensation of $H_2O$.

a) What is the maximum work obtainable from the above process?

b) What would be the maximum work obtainable if the combustion reaction were carried out irreversibly at 1800 °C, but all other steps were reversible?

DATA: For the reaction at 9 atmospheres pressure,

$$\text{CH}_4 + 2 \text{O}_2 \rightarrow \text{CO}_2 + 2 \text{H}_2\text{O}$$

At 25 °C:

$$\Delta H = -208,500 \; \text{cal/gm mole CH}_4$$

$$\Delta S = -1.23 \; \text{cal/gm mole CH}_4/°K$$

At 1800 °C:

$$\Delta H = -211,110 \; \text{cal/gm mole CH}_4$$

$$\Delta S = -4.07 \; \text{cal/gm mole CH}_4/°K$$

Solution:

(a) At 25 °C, $\Delta G = \Delta H - T \Delta S = -208,500 - 298 (-1.23) = -208,140$

To expand 3 moles of products from 9 atm to 1 atm

$$\Delta G = \int \Delta H \; dp = n \int \left( \frac{dP}{P} \right) = nRT \ln \left( \frac{P_2}{P_1} \right) = (3.19) (298) \ln \left( \frac{1}{9} \right) = -3900 \; \text{cal}$$

From Eqn. (16) $\Delta U = \Delta G + 3 \Delta H = -208,140 - 3900 = -212,040 \; \text{cal}$

(b) Irreversible combustion at 1800 °C means that the work which could have been produced in a reversible engine is converted to heat. This could be put through a reversible heat engine to recover some work.

Thus, $\Delta G = -211,110 - (2073) (-4.07) = -202,680 \; \text{cal}$

Using Eqn. (14) $\Delta S = 202,680 / 2073 - 298 = 173,580 \; \text{cal}$

Therefore the lost work due to the irreversible combustion is $202,680 - 173,580 = 29,100 \; \text{cal}$

Net work by this process is

$$W = 212,040 - 29,100 = 182,940 \; \text{cal}$$

No. 4. One hundred lb-mole of a solution of 10 mole percent carbon disulfide and 90 mole percent acetone are to be separated into pure acetone and the azeotrope which forms at 39.25 °C under atmospheric pressure. The azeotrope which forms 61 mole percent carbon disulfide and 39 mole percent acetone.

It is desired to estimate the minimum work to carry out the above separation in a distillation column if the feed solution is all liquid at 39.25 °C and the products are withdrawn as liquids at the same temperature.

At 39.25 °C the vapor pressure of CS$_2$ is 604 mm Hg, while the vapor pressure of (CH$_3$)$_2$CO at the same temperature is 400 mm Hg. At atmospheric pressure the vapor phase may be assumed to behave as an ideal gas. The liquid solution does not behave as an ideal solution, but its activity coefficients may be represented by the Van Laar equation,

$$\ln \gamma_A = \frac{A}{\left( 1 + \alpha \frac{x_A}{x_B} \right)^2}$$

and $\ln \gamma_B = \frac{B}{\left( 1 + \alpha \frac{x_B}{x_A} \right)^2}$

Solution: Let acetone be component A and carbon disulfide be B.

For the equilibrium between the liquid and vapor, Eqs. (20) and (27) show that $\gamma_1^L = \gamma_1^V$. For the liquid $\gamma_1^L = \gamma_1^V$. Taking the standard state as pure liquid under its own vapor pressure and since vapor pressure is low this may be taken as the fugacity $f_1^L = f_1^V$. Also for the gas, assuming ideality, $f_1^G = y_1^G$. Thus,

$$y_1^G f_1^V = y_1^L f_1^L$$

For an azeotrope $x_1 = y_1$ so $y_1^L = \frac{p}{p^L_1}$

Thus,

$$\gamma_A = \frac{760}{400} = 1.90 \; \text{and} \; \gamma_B = \frac{760}{604} = 1.258$$

From equations for Van Laar constants

$$A = \ln A \left[ 1 + \frac{x_B \ln y_B}{x_A \ln y_A} \right]^2 = \ln 1.90 \left[ 1 + \frac{0.61 \ln 1.258}{0.39 \ln 1.90} \right]^2$$

$$= 1.558$$

$$B = \ln B \left[ 1 + \frac{x_A \ln y_A}{x_B \ln y_B} \right]^2 = \ln 1.258 \left[ 1 + \frac{0.39 \ln 1.90}{0.61 \ln 1.258} \right]^2$$

$$= 1.787$$

In feed solution,

$$\ln y_A = \frac{1.558}{1 + 1.558(0.9)}^2 = \ln 1.0202$$

and

$$\ln y_B = \frac{1.787}{1 + 1.787(0.1)}^2 = \ln 4.08$$

From $\Delta G = \Delta G_{\text{ideal}} + \Delta G_{\text{non-ideal}}$ and Eqs. (43) and (44),

$$\Delta G = RT(\alpha \ln y_A + \beta \ln y_B)$$

So

$$\Delta G_{\text{ideal}} = (1.99) (561) [0.9 \ln 0.9 (1.0202) + 10 \ln 0.1 (4.08)]$$

$$= -16,140 \; \text{Btu}$$

(Continued on page 221.)
A Course in Chemical Reaction Engineering

REACTOR DESIGN

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At the University of California, Davis (UCD) two quarter-length (3 lectures/week) graduate courses are available in chemical reaction engineering. The first course, which is required, is a general treatment. The second is an optional offering the contents of which are more specialized and may vary from time to time. The goal of the first course is to complete the outline shown in Table I. However, even though most students have had an undergraduate kinetics course, our experience has been that a semester-length offering would be desirable to cover the subjects listed.

Following each major topic in the outline are references to appropriate books and papers. Together the book references include all the major texts in the field. At UCD several of these (3, 24, 27, 29) have been used as the textbook for the course. On other occasions, the complete list has been assigned as a set of references. We find that even graduate students benefit from thorough familiarity with one reasonably general book.

The course starts out with a review of chemical reaction equilibria to ensure that the student understands how to evaluate equilibrium product distributions. At this time it is also convenient to introduce the interrelations between kinetics and thermodynamics.

The differential conservation equations (Section II) provide the basis for subsequent design of whatever degree of complexity. The equations of motion are generally omitted, to be picked up in context as needed. The energy equation is ordinarily simplified to neglect kinetic and potential energies and shaft work. It is developed carefully in terms of both partial molar enthalpies and temperature, since this seems frequently a source of confusion.

The point material-balance equations also serve to introduce the reaction source term or rate expression. At this point the continuity equation for homogeneous reaction is integrated for constant-volume and variable-volume uniform batch reactors, to stress the nature of the source term in the material balance as a function of instantaneous local properties, independent of the type of constraints on the reacting volume.

The discussion of chemical kinetics (Section III of Table I) is necessarily brief. Students will have had an introduction at least to formal kinetics in undergraduate physical chemistry and chemical engineering kinetics courses. We acknowledge that chemical kinetics in its present state of development is only rarely predictive but often permits more reliable interpolation and limited extrapolation.

The steady-state approximation is discussed fairly thoroughly (2), and its mathematically very valuable consequence—that it reduces a stoichiometrically complex reaction sequence to a stoichiometrically simple reaction—is stressed.

With the information presented the student should be able to follow most of the chemical engineering literature insofar as it attempts to discern reaction mechanisms. On the other hand,
TABLE I. APPLIED KINETICS AND REACTOR DESIGN SUBJECT OUTLINE

References

I. Review of chemical reaction eq. 7, 26, 29

II. Conservation equations for systems with chemical reaction 10
A. Continuity equations with homogeneous reaction
B. Continuity equations with heterogeneous reaction
C. Energy equation

III. Reaction rate expressions 11, 20
A. Material balances with reaction
B. Stoichiometrically simple reactions
C. Stoichiometrically complex reactions
1. Determination of an independent set
2. Analysis of extents of complex reactions
D. Kinetic treatment of reaction mechanisms 6, 17, 23
1. Molecular reactions
2. Steady-state approximation for reactive intermediates
   a. Open sequences
   b. Closed sequences
   (1) Initiation-termination processes
   (2) Constancy of number of reactive intermediates
E. Empirical rate expressions
F. Pseudohomogeneous rate expr. 27

IV. Physical transport and reaction in heterogeneous systems
A. Pseudohomogeneous rate equations—global rate
B. Intrapellet transport
1. Isothermal effectiveness factors 27, 29, 34
   a. Pellet geometry
   b. Reaction order
   c. Criteria for absence of diffusion retardation of rate 27
2. Non-isothermal effectiveness factors 27, 28
3. Physical properties of porous catalysts 29
   a. Surface area
   b. Pore volume, porosity
   c. Pore volume distribution
4. Diffusion in porous media 27-29, 34
   a. Bulk and Knudsen diffusion
   b. Surface migration
   c. Effective diffusivities
5. Heat transfer in porous media 27-29,
   a. Free molecule and normal conduction
   b. Effective thermal conductivity
6. Effect of poisoning on the global rate 34

V. Reactor design
A. Uniform batch reactor
B. Continuous stirred-tank reactor
   1. Steady-state design
   2. Multiple steady states and stability 1, 8, 15
C. CSTR sequences
D. Tubular reactor
   1. Plug-flow reactor
   2. Tubular reactor with homogeneous reaction 12, 13, 31, 32
   3. PFR with axial dispersion 24
   4. Three-dimensional design for packed beds 5
   5. Stability and parametric sensitivity 4, 9, 16, 21
   6. Autothermal operation 15, 18, 19

VI. Transport parameters for packed-bed reactors 5, 27-29
A. Velocity profiles
B. Pressure drop
C. Radial mass and heat transfer parameters
   1. Effective diffusivities and thermal conductivities
   2. Wall heat-transfer coefficients 16
D. Axial mass and heat transfer parameters

VII. Design of fluidized-bed reactors 22, 29, 30
A. Mixing phenomena
B. Models of reactor behavior

VIII. Miscellaneous reactor types
A. Gas-solid non-catalytic reactions 22, 24
   1. Global rate equations
   2. Reactor design
      a. Well-mixed fluid phase
      b. Moving fluid, stationary solid phase
      c. Moving fluid and solid phases
B. Slurry reactors 28, 29
   1. Global rate equations
   2. Reactor design

IX. Non-ideal homogeneous reactors 15, 24, 25
A. Nature of deviations from ideal flow
B. Measurement of residence-time distribution functions (RTD)
C. Modeling actual reactors with PFR and CSTR assemblies
D. Effect on conversion
Teaching, understanding, and applying the principles of reactor design will long remain a major challenge. Students benefit from thorough familiarity with one reasonably general book.

A discussion follows in which the wholly empirical nature of much practical rate data is noted, dealing as it so often does with complex and unanalyzed mixtures, empirical parameters such as research octane number, catalyst deactivation, trace poisons, etc.

Finally, a brief discussion of rate data for heterogeneous reactors, usually treated altogether by homogeneous transport models on a global scale, leads naturally into physical transport questions, that is, Section IV of Table I.

In Section IV effectiveness-factor concepts are first developed, and then their numerical evaluation is investigated. This approach leads conveniently to a discussion of physical properties of porous catalysts, followed by study of diffusion and heat transfer with the effective diffusivity and thermal conductivity the goal. External transport resistances complete this Section. Here care is taken to emphasize the relative importance of heat and mass transport effects for various types of heterogeneous environments such as packed-bed, fluidized-bed, and slurry reactors.

The integral reactor design equations (Section V) are developed rather quickly and little attention is given to their application to isothermal examples. The students are assumed to have had prior experience with this in an undergraduate course. Somewhat more attention is given to non-isothermal cases, since time frequently prohibits adequate consideration of these at the undergraduate level. Particular emphasis is placed on reactor thermal stability. Stirred-tank reactor sequences are discussed briefly, and their use in modeling tubular reactors [e.g., ref. (14)] is noted.

Primary emphasis in Section V is placed on the phenomena which occur in packed-bed reactors. Again, particular attention is given to thermal effects, which Denbigh (15) has emphasized as "undoubtedly the biggest factor of uncertainty in the design of fixed-bed reactors at the present time." Quantitative analysis of these effects requires numerical values for radial and axial Peclet numbers for heat and mass transfer. Empirical correlations and theories for these quantities are discussed in Section VI.

Specific, but practically important, types of heterogeneous reactors are considered in Sections VII and VIII, with fluidized-bed systems singled out for particular emphasis. While gas-solid catalytic and slurry reactors are the only ones listed in Section VIII, it is at this point that other specialized forms can be introduced.

The final subject is non-ideal flow in homogeneous reactors. The time spent here is dependent upon the background of the class. Practical situations where non-ideal flow has a significant effect upon conversion are stressed; for example, the CSTR with one or more internal cooling coils.

RESEARCH IN REACTOR DESIGN

A state-of-the-art graduate course will naturally bare the limitations of our present knowledge, as well as a variety of bypassed problems. A discussion of fluid-solid processes reveals many such areas, both for global rates and reactor design. The role of surface migration, inhomogeneity of catalysts, and heat and mass transfer in real solids are examples, for global rates, of research problems of chemical engineering interest. Work in this area often encounters unusual practical consequences. An interesting recent example is the report of Weisz (33) that catalyst attrition rates in a fluidized catalytic cracking unit can be greatly affected by intraparticle diffusion limitations in the cyclic formation and burnoff of coke deposits. In the design of non-adiabatic packed-bed reactors, uncertainties in the calculation of temperature profiles remain a major source of concern. The scale-up of non-catalytic fluid-solid reactors such as carbon black reactors and lime kilns is hindered because of lack of research on mixing patterns. Many computational difficulties remain in the design of integral reactors because of the complexity of boundary conditions in heterogeneous systems.

Research on the design and operation of reactors for treating both municipal and industrial waste water is of literally vital significance. Improvement in the operation of biological reactors for treating primary effluents is an urgent need. New schemes are needed for the treatment of secondary effluents, and the chemical-reaction route offers many advantages. The design of photochemical reactors, which offer a new kind of nonuniformity, that of the light intensity, is an area of active research.

Though by no means exhaustive, these research areas are illustrative of both the work basic to reactor design yet to be done and the demanding
practical needs of society which application of our knowledge of reactor design offers hope of meeting. Teaching, understanding, and applying the principles of reactor design will long remain a major challenge to chemical engineers.

REFERENCES


PROBLEMS (Cont’d from p. 217.)

\[ \Delta G_{\text{products}} = \Delta G_{\text{azeo}} + \Delta G_{\text{acetone}} - \Delta G_{\text{azeo}} \]
\[ \Delta G_{\text{azeo}} = (1.59) (561) \left[ \frac{16}{61} \right] \ln(0.39) (1.9) + 10 \ln(0.61) (1.258) \]
\[ = -5,550 \text{ Btu} \]
\[ W_k = \Delta G = \Delta G_{\text{products}} - \Delta G_{\text{feed}} \]
\[ = 5050 + 18140 = 13090 \text{ Btu/100 moles feed} \]

No. 5. Badische Anilin and Soda-Fabrik AG of Ludwigshafen am Rhein give this data.

*Water-Gas Shift Reaction—Conversion of the carbon monoxide proceeds according to the expression:

\[ \text{CO} + \text{H}_2 \text{O} \rightarrow \text{CO}_2 + \text{H}_2 \]
\[ \Delta H = -9,810 \text{ cal} \]
It is an equilibrium reaction with a temperature-dependent equilibrium constant,

\[ K_p = \frac{[\text{CO}] [\text{H}_2]}{[\text{CO}_2] [\text{H}_2]} \]

FALL 1969

The location of the equilibrium for a given gas composition is independent of the total pressure of the system.* Also presented with the above statements is a graph which is reproduced below. Please study this information and demonstrate (a) by numerical calculations whether their data are concordant, and determine (b) the free energy change of the reaction at 500°C.

\[ \text{Temperature dependence of the equilibrium constant } K_p \]

\[ \text{Assume } K_p = K_a \]

(Continued on page 226.)

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Perhaps at no time in its history has engineering education been beset by as many problems as exist today. It has been said from many directions that those who left engineering teaching as much as fifteen years ago would not recognize much of the course material taught today. Although this may be somewhat of an exaggeration we recognize its broad validity, and we must look forward to equally rapid changes in the future. A vice-president of one of the great electrical concerns mentioned when talking to students that his company based its long-term planning on the assumption that one-half of its business twenty years from now would be in new products. To transfer this concept to engineering education we might anticipate that one-half of the courses in the engineering college catalogs circa 1985 will be totally new subject matter and the remainder will be considerably altered.

Because college catalogs are revised every year faculties are used to the concept of new courses and curricular changes. The picture of a fifty percent change in course material in fifteen years is not startling because it represents a normal evolutionary trend. In fifteen years the volume of published scientific and engineering material will at least have doubled. There are other changes which are just as probable that appear to produce very severe emotional reactions even when they are merely discussed. Such questions as, what should represent the first professional degree in engineering, and how does technician training articulate with engineering education are highly sensitive areas of interest. These areas require objective analysis which is difficult to achieve because of emotional reactions based upon the concept of a unified profession that has never truly existed in engineering. We wear blinders if we fail to recognize that technicians continually, although in small numbers, move upward into the engineering profession, and that scientists move laterally with little resistance into engineering activities. Both groups achieve the title of engineer in industry. Engineering is a profession in flux that has still not been defined for the purpose of exclusion either by words or more importantly by actions.

An agency involved deeply with the need to define the undefined and perhaps undefinable profession of engineering is the Engineers' Council for Professional Development. Its task of accrediting engineering curricula and therefore degrees has successfully placed a floor under the profession of engineering that has received broad acceptance. However, this floor, based upon the amount of engineering education that can be mastered in four academic years while allowing for required work in mathematics, science, and social-humanistic studies is not highly restrictive. The great majority of institutions that make an
The evidence seems to point to the master's degree evolving rather gradually into the main accredited degree whether or not it is called the first professional degree.

Effort to recruit an engineering faculty of reasonable quality, who in turn select students of reasonable competency, achieve accreditation. Their products become engineers by definition, and those scientists and technicians who retrain or upgrade themselves to compete with the product of the engineering schools are accepted as engineers.

Under the procedures just described, we seem to have some 800,000 engineers in this country, of which about one-half belong to a major engineering society. A 1967 EJC survey determined that 565,000 individuals belonged to 45 technical and professional societies, of an engineering and applied science nature, of which 438,000 were classified as engineers. The technical societies that hold membership in ECPD and EJC do not all restrict their membership to engineers.

GRADUATE ENGINEERING ACCREDITATION

An old refrain in engineering education has been the five-year undergraduate curriculum. It has been proposed, urged and tried over a forty-year period without significant success. At times it appeared that nearly a majority of faculty members would favor it. Why then has there been so much emotional resistance to the concept of the master's degree becoming the “first professional degree”? It seems doubtful that the resistance rests upon the concept that future professional engineers can attain an adequate education in four years. Such is patently not true. It may be that the terminology of “first professional degree” applied to the master's degree raises the specter that a very large fraction of presently practicing engineers would lose professional status. Because only a quarter of practicing engineers now have master's degrees a long transition period would be inevitable. Terminology can often mask the most desirable objectives.

It is becoming evident that the Engineers’ Council for Professional Development is gradually being drawn into graduate accreditation in a step-by-step fashion. The first step over a decade ago was to accredit the master's programs of the Naval Postgraduate School using undergraduate standards. Then a number of master's degree programs or curricula developed in engineering departments having no undergraduate curricula. These departments applied for accreditation and were gradually accepted. Now there are requests for accreditation of master's level curricula in colleges that offer bachelor's degrees in engineering where the bachelor's program is considered to be pre-professional by the institution concerned. ECPD certainly cannot insist upon accrediting a pre-professional curriculum, and it is doubtful that it can logically reject the right of any educational institution to define for itself what it wishes to call its first professional degree in engineering.

The evidence seems to point to the master's degree evolving rather gradually into the main accredited degree whether or not it is called the first professional degree. Important influences are the following: (1) It seems doubtful that a four-year education in engineering can be made sufficiently superior to four years of either science or technology to form the base for a clearly defined profession. (2) An accredited master's degree program based upon student desire and aptitude for advanced study, with the opportunity for those whose interests are not highly professional to accept employment at the bachelor's level, would aid greatly in defining the profession of engineering. Quite independent of emotional reactions this seems to be the most probable direction of gradual evolution. This change will be stimulated by changes in the engineering college catalog because the course material added always exceeds the deletions. Additions can be made at the master’s level without gross economic waste due to greater motivation of selected and self-selected students.

A factor that should not be overlooked in the accreditation of graduate education is its usefulness in upgrading the casual offerings at many off-campus centers. Undergraduate work in the evening was at one time taught mainly by industrial employees on a part-time basis. Undergraduate work in the evening was at one time taught mainly by industrial employees on a part-time basis. Gradually through the accreditation process evening study has been upgraded to achieve as nearly as practical an equivalency with day curricula and day procedures. At the graduate level there has been a dissemination of degree work to so-called graduate centers. These centers operate not only under the difficulties of evening programs on an over-time basis, but they often use part-time teachers to an excessive degree. Many fail to
provide even the minimum essentials of library or laboratory resources. Until graduate accreditation in engineering becomes accepted, these graduate centers will lack standards to guide their activities. They need and their students deserve the support that professional accreditation would provide. Unfortunately, we still cannot provide the upgrading through accreditation that the off-campus graduate programs so clearly need.

TECHNOLOGICAL ACCREDITATION

At the opposite end of the spectrum from graduate-engineering accreditation is found the problem of technology curricula accreditation. Beginning with the Wickenden report in the late nineteen twenties it has been recognized that the productivity of engineers depends upon the number and quality of the technicians available as engineering assistants. In World War II the engineering colleges became large scale technician training agencies for the Federal Government and made one of their greatest immediate contributions to the war effort through this channel. A post-war surplus of technicians may have existed for a time, but if so, this could have been only at the lower levels. The United States has never developed an educational system that has produced high-level technicians comparable to those produced in most European countries. Instead, our bachelor degree engineers have performed many technician-level activities.

This country suffers under the status symbol of the bachelor's degree. Parents make great sacrifices for their children to attain degrees. Any degree often appears acceptable. Hence technician curricula ranging from two to three years have never attracted sufficient numbers of students. The result is that new degree-level programs in technology have been growing in numbers. They now represent a considerable group of curricula that carry the same descriptive titles as the branches of engineering, i.e., electrical, mechanical, etc. One technological curriculum widely adopted is building construction, which found a home in colleges of architecture rather than engineering. It has in part superseded the curriculum of architectural engineering which was technically too demanding upon the type of student who was interested in this field.

The curriculum of building construction provides the degree incentive and the reward of desirable employment in a status position ultimately directed toward supervision without requiring the rigor of an engineering curriculum. It has grown rapidly in popularity and is entirely outside the control or direction of the engineering profession.

The broad field of industrial technology based educationally upon degree curricula now seems to be ripe for a development comparable to the example given of building construction. The engineering profession can influence this development through its procedures of accreditation or it can stand aside and observe the uncontrolled development of a second channel for the preparation of technological personnel. When this problem was presented by the establishment of associate-degree technician training curricula in the years immediately following World War II it was decided to lend a hand toward strengthening these technical curricula through ECPD accreditation. Of course, the question of terminology arose, in particular the use of the adjective engineering to describe such curricula. Obviously ECPD could serve no function in the field of medical technology or other fields not directly related to engineering. Our interest had to be restricted to the training of engineering technicians. To make this clear the curricula eligible for ECPD accreditation were classified as "engineering technology" curricula. However one may feel about the terminology chosen, the logic involved seems indisputable. Unless a technical curriculum is designed to produce technicians who will work directly with engineers it could hardly fit within the objectives of ECPD.

The recent action of the Board of Directors of ECPD to accredit engineering technology curricula of two, three and four years duration upon the single basis of inspection of about 70 credit hours of technical course work merely fulfills the concept described above. Beyond the required and regulated core of some 70 credit hours the institution may decide to add additional work requirements to justify the award of a bachelor's degree. This additional work may be in liberal arts, business administration, further technical courses in the major, or in a second specialty, or in any combination it may choose. ECPD will restrict its interest to the core program that
Six Good Reasons To Choose A McGraw-Hill Text

OPTIMIZATION THEORY AND PRACTICE
GORDON S. G. BEVERIDGE, Heriot-Watt University, Edinburgh and ROBERT S. SCHECHTER, University of Texas. Available Winter, 1970

This text encompasses techniques from all aspects of mathematical optimization with the objective of introducing these methods to seniors and graduate students. It is organized to illustrate the interrelationships among optimization methods, their ranges of applicability, and their comparative effectiveness. The authors provide fully worked-out examples throughout the book to aid the student, and discuss the main techniques in detail to give the student competence in their applications.

OPTIMIZATION BY VARIATIONAL METHODS
MORTON M. DENN, University of Delaware. 416 pages, $16.50

In order to present a comprehensive examination of optimal process design and control, the author has simultaneously developed both analytical and computational considerations and then united them with detailed practical applications. The text utilizes the "variational" approach, incorporating traditional differential calculus procedures and associated computational techniques; classical calculus of variations; Pontryagin-type "minimum principles" and related computational methods; and dynamic programming. Many of the examples cited are examined at various levels of sophistication and solved by several different procedures.

ENGINEERING THERMODYNAMICS
WILLIAM C. REYNOLDS, Stanford University and HENRY C. PERKINS, University of Arizona. Available Winter, 1970

The first half of this book develops the fundamentals of thermodynamics using microscopic insight as the basis for macroscopic postulates. Disorder, randomness, and uncertainty notions are used in conjunction with the Gibbs definition of entropy to provide an intuitive basis for the second law postulate. The remainder of the book applies the statistical concepts that have already been developed to actual engineering systems. Material on power systems and chapters on compressible flow and heat transfer are included.

ENGINEERING DIFFERENTIAL SYSTEMS
ROBERT D. KERSTEN, Florida Technological University. 224 pages, $13.50

This is the first book to treat both the analytical as well as the numerical methods in engineering. The author's thesis is that a complete solution to a given engineering differential system can be developed by using these approaches to connect four essential parts of the system: (1) properly understood phenomena; (2) a correct mathematical model of the phenomena; (3) a tentative solution; and (4) a proper application of boundary or initial conditions or both.

DESCRIBING CHEMICAL ENGINEERING SYSTEMS
WILLIAM E. RANZ, University of Minnesota. Available Winter, 1970

With the intention of demonstrating how physical and mathematical models are built, this participation textbook discusses states and actions of physical and chemical systems; shows the detailed development of material and energy balances; and includes interactions of simple connected systems as they are applied to chemical engineering. This workbook is based on the premise that a student learns by doing—therefore, numerous questions and worked-out examples dominate the text.

MODERN METHODS OF ENGINEERING COMPUTATION
ROBERT L. KETTER and SHERWOOD P. PRAWEL, JR., both of the State University of New York at Buffalo. 500 pages, $15.50

This text (1) presents an introduction to the field of modern computational methods in terms intelligible to the second- or third-year student; (2) develops from these various methods the first principles that are basic and/or in general usage and indicates the interrelationships among them; and (3) views the material specifically but yet generally enough to give the student the background he will need in numerical methods to cope with future engineering courses. Throughout, the emphasis is on the methodology of the solution process and the universality of its application to problems in all fields of engineering and the applied sciences.
relates directly to the title of the curriculum. The award of a degree will be primarily the interest of the regional accrediting agency. Regional accreditation at the appropriate level (associate or bachelor's degree) must precede ECPD inspection. It is believed that this limited accrediting procedure by ECPD will eliminate, to the maximum degree possible, confusion between engineering education and engineering technician education.

RECOGNITION OF CONTINUING EDUCATION

The significance of continuing education for engineers was recognized a few years ago by a comprehensive report sponsored by EJC, ECPD, ASEE and NSPE that emphasizes its great importance to the engineering profession. Nevertheless, continuing education operates under the handicap that the achievement of the individual receives no formal recognition. In contrast, a reasonable amount of effort directed toward part-time graduate study can result in a master's degree that receives nation-wide acceptance. If some type of formal recognition of perhaps an equivalent academic year of effort devoted to continuing education could be developed, the attention given to continuing education would doubtless increase. Because of its extensive experience with the accreditation process, ECPD seems to be the logical agency to experiment with this concept of formal recognition of achievement in continuing education. It is hoped that an appropriate channel for such recognition may be devised. It seems to the writer that such recognition is a serious responsibility of the engineering profession that has been neglected merely because of its sensitive nature.

DEFINING A PROFESSION

A profession may be defined in part by required steps of admission and advancement of its members. It can also be defined in part through aiding in the recognition of associated groups, who relate clearly to its activities, but by using distinctly different standards for recognition. Such a relationship exists between engineers and engineering technicians or technologists. There is reason to hope that these and other actions of engineering societies may aid in defining the profession of engineering which has resisted inclusive definition by words alone. Nevertheless, the writer believes that definitions can be improved.

PROBLEMS (Cont'd from p. 221.)

Solution:

(a) Assuming heat capacity effects negligible, use Eqn. (30) in the form

\[ \ln K_a = \frac{\Delta H^0}{R} \left( \frac{1}{T_1} - \frac{1}{T_2} \right) \]

From the graph \( K_a = 0.1 \) at 427°C and 0.4 at 600°C

Thus \( \Delta H^0 = \frac{(1.99)(773)}{(117) \ln 0.4} = 9750 \text{ cal/gm mole} \)

This agrees well with the -9810 cal given. The slope of the \( \ln K_a vs 1/T \) plot gives the same result.

(b) At 500°C, \( K_a = 0.19 \) for \( CO_2 + H_2 \rightarrow CO + H_2O \)

For the reverse reaction \( K_a = \frac{1}{0.19} \)

Therefore, from Eqn. (29)

\[ \Delta G^0 = -RT \ln K_a = -(1.99)(773) \ln \frac{1}{0.19} \]

\[ = -2550 \text{ cal/gm mole} \]

No. 6. The heat of combustion of hydrogen with oxygen at atmospheric pressure and 18°C to form liquid water is 68,000 cal/gm mole \( H_2O \). The reversible voltage for the electrolysis of water in a very dilute acid solution at 18°C is -1.23 volts when all products and reactants are at atmospheric pressure. The latent heat of vaporization of water is 10,500 cal/gm mole, and both this and the heat of combustion vary negligibly with temperature. The vapor pressure of water at 18°C is 15.48 mm Hg (neglect effect of small acid content), while at 40°C the vapor pressure is 55.31 mm Hg.

Calculate the reversible voltage to electrolyze water at 40°C if the products and reactants are at 5 atm pressure. Assume ideal gas behavior and negligible effect of pressure on vapor pressure. For water take the standard state to be (a) pure liquid under atmospheric pressure and (b) pure gas under its vapor pressure at 18°C. Compare the two answers. The reaction is \( H_2O \rightarrow H_2 + \frac{1}{2} O_2 \)

\[ \Delta H^0 \]

\[ \frac{\Delta F^0}{F} = \frac{\Delta H^0}{F} \]

or

\[ \Delta F^0 = -1.23(313) + 68,300(313) \left( \frac{1}{241} - \frac{1}{291} \right) \]

\[ = -1.211 \text{ volts} \]

By Eqn. (35)

\[ \varepsilon_r = \frac{\Delta F^0}{1/2 \ln a_{H_2O}} \]

\[ = -1.211 + (1.99)(313) \ln \frac{57,800}{22,050} = -1.2438 \text{ volts} \]

In producing gaseous water \( \Delta H = 68,300 - 10,500 = 57,800 \text{ cal/gm mole} \)

Thus, \( \varepsilon_r = \frac{-1.23(313) + (57,800)(313)}{2241} = -1.228 \text{ volts} \)

Now activity of gaseous water under own vapor pressure is

\[ a_{H_2O} = \frac{15.48}{22.48} = 0.69 \]

So

\[ \varepsilon_r = -1.228 - (1.99)(313) \ln \frac{1}{22.48} = -1.2434 \text{ volts which agrees well with -1.2438} \]

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THE CHEMISTRY-CHEMICAL ENGINEERING MERRY-GO-ROUND

RALPH A. MORGEN
Stevens Institute of Technology
Hoboken, N. J.

The major characteristic which distinguishes the chemical engineer from all other engineers is the foundation in chemistry which is required. There is a generally accepted statement, the origin of which has been lost in antiquity, that says “The day mechanical engineers dropped physical chemistry from their curriculum, chemical engineering was born.” Since the birth of the AIChE, the question of chemical engineering education has been uppermost in the minds of its members. One of the first acts of the new Society was to establish a committee on Chemical Engineering Education, under the Chairmanship of C. F. McKenna. There was much debate on the curriculum content for chemical engineering but little consensus until after World War I, which has been known by many people as the “Chemists’ War.” Prior to that war, there was little chemical industry in this country. As a matter of fact, the United States was so dependent on foreign imports of chemicals that the Germans were encouraged in 1915 to deliver a supply of dyes to the United States by submarine to avoid the Allied blockade. Following the “Chemists’ War” there was a major increase in the chemical industry. Along with the growth of that industry, there was a demand for chemists and chemical engineers to staff these industries.

The fundamental educational debate at that time was whether or not there really was such a thing as chemical engineering. That chemists were employed in the chemical industry was unquestioned. That engineers were employed in the chemical industry was unquestioned. The German concept was to have a team of a chemist and a mechanical engineer perform most of the functions that are today thought of as chemical engineering. It remained for the team of William H. Walker, W. K. Lewis, and W. H. McAdams to publish a textbook “Principles of Chemical Engineering” in 1923, to clearly and succinctly delineate, for the first time, the place of chemical engineering. This book made a clear distinction between the industrial chemists on the one hand and all other engineers on the other. The most significant contribution of Walker, Lewis and McAdams was to focus the attention of chemical engineers on the unique place of the unit operations. While the term ‘unit operation’ had been used earlier and is credited to Arthur D. Little, who based a curriculum study on unit operations as early as 1915, the concept did not take hold until after the publication of this book. Dr. Little, while he was Chairman of the Chemical Engineering Education Committee of AIChE, made the first steps towards the establishment of accredited chemical engineering curricula. This initial list appeared in 1925, eight years before the rest of the engineering profession established the Engineers’ Council for Professional Development. Only fourteen institutions appeared on this list. In 1933, the chemical engineers joined ECPD, but they retained a certain amount of autonomy. They were the only ones who, because of their previous experience, saw the necessity for greater emphasis on the basic sciences in the undergraduate curriculum followed by advanced work at the graduate level. This occurred before World War II, commonly known as the “Physicists’ War.”

Ralph A. Morgen is a graduate of the University of California, Berkeley (PhD ’25). He has been active in research, teaching, and administration in engineering education for thirty years. His most recent assignments were President of Rose Polytechnic Institute and Dean of Graduate Studies at Stevens. Currently he is an engineering consultant to Florida Atlantic University.

IN ORDER TO EVALUATE WHAT HAS happened to the chemistry content of the undergraduate curriculum over the past 30 years, the 14 institutions on the original accredited list augmented by those institutions which were deemed to have either distinguished or strong faculties in the American Council on Education study have been reviewed. The conclusions in this paper have been confirmed by reviewing what has happened to the chemistry content of these twenty-four institutions.

From 1925 until accreditation was temporarily abandoned during World War II in 1943, there was general pulling and pulling among the proponents of more chemistry and basic sciences as opposed to those who preferred more applied and more practical engineering emphasis in the curriculum. Dr. Albert B. Newman summarized the situation as it existed in the late 1930's very well. Quoting from that paper:

"In modern practice, it seems clear that the chemical engineer must not only have a working quantitative knowledge of the unit operations, but he must have a sound knowledge of chemistry, physics, mathematics, thermodynamics and economics. He must have facility in applying physical chemistry to plant processes, particularly in relation to reaction velocities and the graphical calculus used in the interpretation of laboratory and pilot plant data on kinetics of chemical reactions."

As a result, in order to try to satisfy the two opposing views, more engineering and applied courses versus more chemistry and basic sciences, the credit content of the undergraduate chemical engineering course rose to an almost intolerable level at many of the institutions. In some cases, an average of 20 semester credit hours for a total of eight semesters was required for graduation. The four year curriculum was reaching the bursting point. Most of the stronger accredited institutions, in that period, insisted on four years and a summer session, usually between the junior and senior years, to lessen this unrealistic load. The Chemical Engineering Education Committee was far ahead of the education committees of the other engineering societies and of the philosophy of ECPD in two respects in the 1930's. The chemical engineers did not consider the four year undergraduate course as terminal education, but rather "that education has just begun at the end of the four year course. No student should prepare for chemical engineering unless he is enthusiastic about the idea of a lifetime of study." The Committee further believed that research activity by the chemical engineering staff and graduate students is important and was usually found in those institutions which qualified for accrediting.

IN FACT, THE TRADITION OF GRADUATE WORK in chemical engineering was one of the close ties between chemists and chemical engineers which fostered graduate education in both disciplines following (World War I). The recommended content of an undergraduate chemical engineering curriculum in 1938 is shown in Table I. The percent figures are those taken from Newman's publication. There was little dissension regarding the percentages, but the difficulty arose when such a curriculum had to be translated into a reasonable number of credit hours. For convenience, in Table I, the column of normal credits is given for comparison with present day curricula, but many of the actual curricula contained total credits up to 160. It appears, therefore, that in the 30's, most of the accredited curricula included four whole year courses and at least one additional one semester course in chemistry. The year courses were usually general chemistry, quantitative analysis, organic chemistry and physical chemistry. The additional courses varied widely depending on the interests, competence and backgrounds of the faculty at the various institutions. At this time, it was generally agreed that the undergraduate load was too heavy and further that graduate work was to be encouraged. Quoting again from Newman's paper: "The Committee is of the opinion that the tendency to extend chemical engineering study into graduate years, especially on the part of those students whose special aptitude in theoretical divisions, is one that should be

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3Development of Chemical Engineering Education in the United States, Supplement to transaction of the American Institute of Chemical Engineers, Volume 34, No. 3A, July 25, 1938.
4Ibid. Pg. 12
5 Ibid. pg. 16
6 Ibid. pg. 23.
7 Ibid. pg. 23.
It appears that the ChE Education Committee in 1938 reached the conclusion which apparently the rest of the engineering profession is tentatively approaching in 1967.

There was general agreement in the thirties that if the amount of chemistry in the chemical engineering curriculum is reduced drastically, then the need for chemical engineering as a separate entity becomes academic. This was about the situation when World War II intervened. A temporary cessation of the accrediting function took place between 1943 and 1946. When the ECPD Education and Accreditation Committee reconvened after World War II, the effect on the undergraduate engineering curricula was obvious to many. The engineering education of the 30’s was found to be insufficient in its content of mathematics and the basic sciences. The need for adding large doses of the engineering sciences (which the chemical engineers had called unit operations in their area for many years) became obvious. The physicists became enamored with sub-atomic phenomena and tended to abandon classical physics. Thus, the engineering sciences and much of classical physics tended to merge. The resulting effect on the chemistry content of the chemical engineering curricula was serious and in some cases drastic.

It became obvious that a thorough re-study of the needs of undergraduate engineering education was in order. At the request of ECPD, ASEE undertook a study which has come to be known as the Grinter Report. The report of this committee reads strikingly similar to the recommendations of the Committee on Education and Accreditation of AIChE as announced by its chairman in 1938. The obvious difference, however, is that when most of the members of the Grinter Committee talked about the basic sciences and the engineering sciences, they were almost uniformly talking about physics and almost uniformly neglecting chemistry. It was only through the valiant effort of the few chemical engineering members of the ASEE Commit-

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TABLE II — COURSE CONTENT RECOMMENDED BY THE COMMITTEE ON EVALUATION OF ENGINEERING EDUCATION\(11\) 1952-1955

<table>
<thead>
<tr>
<th>Proportion of Curriculum</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Humanistic Social Studies</td>
</tr>
<tr>
<td>(2) Mathematics and Basic Sciences</td>
</tr>
<tr>
<td>(3) Engineering Sciences</td>
</tr>
<tr>
<td>(4) Sequence of Engineering Analysis, Design and Engineering Systems, including the Technological Background</td>
</tr>
<tr>
<td>(5) Options or Electives</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

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\(10\) Ibid.

curriculum on one side, decrease the total number of contact hours on the other side and still make an engineering curriculum without going beyond four years. The conclusion is obvious. Sooner or later it must be recognized that an adequate four years curriculum in chemical engineering is a misnomer. The Goals of Engineering Education Committee realize that there are many ways to reach the desired objective of a well educated professional engineer. However, in each case the inescapable conclusion must be reached that an engineer has an insufficient background at the end of the Bachelor's degree program to fit him for a productive technical career in engineering. The report further contends that formal education to the Master's level followed by continuing education throughout his professional life is a must for the engineer of the future. Equating the Goals report to chemical engineering it appears that there is room for various kinds of chemical engineering curricula, all the way from a very “light” chemistry content at the undergraduate level followed by more chemistry at the graduate level to a “strong” chemistry content at the undergraduate level followed by more engineering at the advanced level. (See Table III)

TABLE III — FOUR YEAR COMPROMISE BChE CURRICULA

<table>
<thead>
<tr>
<th>Light Chem.</th>
<th>Strong Chem.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semester cr.</td>
<td>Semester cr.</td>
</tr>
<tr>
<td>Mathematics</td>
<td>21</td>
</tr>
<tr>
<td>Chemistry</td>
<td>24</td>
</tr>
<tr>
<td>Other Science</td>
<td>12</td>
</tr>
<tr>
<td>Chem Eng Science</td>
<td>34</td>
</tr>
<tr>
<td>Other Eng Science</td>
<td>10</td>
</tr>
<tr>
<td>Chem Eng Design</td>
<td>9</td>
</tr>
<tr>
<td>Other Eng Design (Electives)</td>
<td>6</td>
</tr>
<tr>
<td>Humanistic-Social</td>
<td>28</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>144</strong></td>
</tr>
</tbody>
</table>

If a four year curriculum in chemical engineering is to continue to be the norm for first accreditation and if the student is not to be given an intolerable overload, then some compromises must be accepted. A reasonable compromise can be achieved among the relative amounts of basic science (in this case the amount of chemistry), the engineering sciences and the analysis, synthesis and design sequences. This compromise is coupled with the assumption that a course load greater than 18 credits per semester or 144 semester credit hours for four years is undesirable.

The “light chemistry” curriculum provides for a year course each in general, organic and physical chemistry. This is agreed as the irreducible minimum for a chemical engineer. The “strong chemistry” program allows for about three semesters of additional chemistry, but in so doing some mathematics, chemical engineering science and chemical engineering analysis, design and systems must be sacrificed. The twenty-three institutions in Table II with accredited undergraduate chemical engineering curricula in 1967 all come within these limits.

Once the young Bachelor's degree recipient from either of these curricula becomes engaged in technical work in industry, he will feel his inadequacy in one direction or the other depending on his needs. He will be encouraged by his employer to fill the gaps by proceeding to the Master's degree. A typical program (See Table IV) illustrates how either man can reach the same general Master's degree plateau by selecting the appropriate courses.

There is considerable question in this writer's mind whether the graduate from the “strong chemistry” curriculum (which contains the minimum amount of chemistry recommended by AIChe in the 30's) has sufficient engineering content to justify a designated degree (or an accreditable degree) in chemical engineering. The “light chemistry” curriculum has a reasonable engineering content but is shy in chemistry. The problem has now come full circle. When the AIChe Committee on Accreditation published its first accredited list in 1925, the concern was to

TABLE IV — THREE POSSIBLE ROUTES TO THE MChE DEGREE

<table>
<thead>
<tr>
<th>Basic Gen. Eng Degree</th>
<th>Light Chem. 1st Prof Degree</th>
<th>Strong Chem. 1st Prof Degree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mathematics</td>
<td>22</td>
<td>21</td>
</tr>
<tr>
<td>Chemistry</td>
<td>28</td>
<td>24</td>
</tr>
<tr>
<td>Other Science</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td>Ch.E. Science</td>
<td>22</td>
<td>34</td>
</tr>
<tr>
<td>Other Eng. Science</td>
<td>18</td>
<td>10</td>
</tr>
<tr>
<td>Ch. Eng. Analysis, Design and Systems</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>Other Eng. Analysis, Design and Systems</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Humanistic-Social</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>144</strong></td>
<td><strong>144</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1st Prof Degree</th>
<th>2nd Prof Degree</th>
<th>2nd Prof Degree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mathematics</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Chemistry</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>Chem Eng Science</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Chem Eng Analysis, Design and Systems</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td>(includes thesis)</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>
distinguish the chemical engineer as an engineer distinct from the industrial chemist. Now the problem appears to be to provide the chemical engineer with enough chemistry to distinguish him from other engineers.

As early as the 1900's, Newman and his Committee recognized that education beyond the Bachelor's level was required if the chemical engineer were to have both sufficient chemistry and engineering. The intervention of the Physicists' War showed everyone the need for basic physics for all engineers. Thus, at the time of the Grinter Report in 1955, the amount of basic science in all engineering curricula was raised for the first time to the level required by the chemical engineers as early as 1933. The net result has been that chemical engineering, in order to increase the physics content, had to decrease the chemistry content. The Grinter Report recommended that an engineering curriculum include in the more general engineering sequence in favor of engineering science courses in other departments, i.e. fluid dynamics in place of the unit operations label. The result is a squeeze in the chemical engineering sequence in favor of engineering science courses in other departments, i.e. fluid dynamics in place of the unit operations fluid flow. Conversely, some very fine courses in high temperature chemistry are being conducted by departments of aeronautics and aeronautical engineering and some courses in radiation chemistry are being taught by departments of physics and nuclear engineering rather than departments of chemistry. Thus, many of the old labels are being confused.

At this point, it does not seem desirable to debate the virtues and vices of these changes, but merely to report them as facts. The result is similar to the meeting of the immovable body and the irresistible force. Somebody has to give or the result is chaos. This writer favors a compromise solution in which all engineers will be given a Bachelor's degree in engineering undesignated. Each student in the general engineering curriculum (See Table IV) would be given sufficient latitude in electives so that he can choose the basic science and the engineering science that will give him a sufficient flavor of his proposed major. At the same time, the concentration in his major would be limited so as to permit his getting a broader engineering education than would be the case if there were a designated degree at the Bachelor's level. With this type of broad engineering degree, the first designated degree would be at the Master's level. It should be a stronger degree with a broader background than would be the case with a Master's degree built on either the "light chemistry" BChE degree or the "strong chemistry" BChE degree. (See Table IV for comparison).

Nevertheless, it seems perfectly clear that there are at least three routes toward the Master's level in chemical engineering, any one of which will produce a satisfactory product. It is also evident that more chemistry is needed by the chemical engineer than he is now getting in many of the "light chemistry" BChE curricula in institutions listed in Table III. It is further assumed, however, that the better students are wise enough to get that chemistry either by taking additional courses after they graduate or are being exposed to this material by taking courses otherwise labeled in other departments.

The inevitable conclusion is that the explosion of knowledge since World War II has emphasized the importance of giving to the present day chemical engineer at least as much chemistry as he had before World War II. In addition, his curriculum must include more from the other basic sciences plus more mathematics as well as new and expanded engineering sciences. If he is to be an engineer, he must have his share of courses in analysis, and design. All this material cannot fit in the old standardized package.

There will be ample jobs for anyone who wishes to terminate his formal education at the traditional Bachelor's level. All three routes, the "light chemistry" BChE, the "strong chemistry" BChE and the general engineering with chemical electives BE, will find many opportunities for productive careers. But in 1967, as in 1938 the chemical engineer has just begun at the end of four years of formal study. No student should prepare for chemical engineering unless he is prepared for a life-time of study — with a maximum of chemistry.

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12Tbid. pg. 23
LETTERS (Cont'd from p. 208.)

Wills surveys publication frequencies

Sir: Publication of the results of their continuing research is a major responsibility of those holding academic positions in the field of Chemical Engineering. Frequently, and at least once a year during salary review, questions arise concerning these scholarly publications. Presumably both individuals and departments as a whole are evaluated. While it is possible to determine an average performance for an institution, for its component schools and departments, it is not ordinarily possible to compare individuals and departments with their peers (i.e., similar departments and disciplines at other institutions) even though this would be highly desirable. The deficiency in the use of peer-comparison is due to the lack of suitably detailed statistics for each discipline. The purpose here is to furnish the data necessary for peer-comparison in the field of Chemical Engineering.

Detailed reporting of publications by departments and by individuals is available for ChE for the two year period July, 1965 to July, 1967. The source of this information is the 'Directory of Graduate Research,' published by the ACS. The information contained in this publication was solicited directly from all of the ChE departments in the United States offering graduate degrees.

While detailed information concerning publication records is available in the ACS "Directory of Graduate Research", there is no statistical correlation of these data. Given here is a correlation of these data. The publication records by professional rank are given in Figures 1, 2 and 3. Figure 4 gives overall departmental records. Table 1 gives additional information concerning the publication data.

It should be pointed out that the estimates of publications should be considered as slightly inflated due to the reporting of items that ordinarily would not be considered publications. However, some editing has been done in this regard and the distributions and averages shown should be substantially correct. Also, the data correlated reflect the period 1965-67. The decreasing graduate enrollments of the past two years may well result in a reduction in the current rates of publication.

George B. Wills
Virginia Polytechnic Institute

Table 1. Publication Rates in 78 ChE Departments

<table>
<thead>
<tr>
<th>Professors</th>
<th>Number</th>
<th>Pub. per man-yr.</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assistant</td>
<td>229</td>
<td>0.73</td>
<td>11.3% published 2 or more papers/yr.</td>
</tr>
<tr>
<td>Associate</td>
<td>216</td>
<td>1.09</td>
<td>10.2% published 3 or more papers/yr.</td>
</tr>
<tr>
<td>Full</td>
<td>308</td>
<td>1.95</td>
<td>10.1% published more than 4 papers/yr.</td>
</tr>
<tr>
<td>Avg.</td>
<td>(78 depts.)</td>
<td>1.27</td>
<td>9.0% of all depts. pub. 2.25 or more papers/yr.</td>
</tr>
</tbody>
</table>

FALL 1969
ACROSS
2. Berkeley overlooks beautiful San Francisco.
5. The Athens of the West.
9. City on Monterey Peninsula, 3 hrs. south of Berkeley.
11. California State University.
12. Telegraph Avenue is a large street.
14. Recent basketball star for Cal, had vulgar outburst at game.
15. People over 30 are likely to be 
16. Principle item developed during this research.
23. Noted early Californian.
27. French deli.
30. Call occasionally scores one in Memorial Stadium.
33. Initials of American Conservatory Theater, noted San Francisco repertory group.
34. Graduate students do spend time here.
35. First letter of 41 Down.
36. Prominent resident of Carmel by the Sea, located near Berkeley.
37. Opened up that Golden Gate.
38. True of Berkeley campus.
41. San Francisco airport.
43. The Queen of England.
45. The _______ and found of the Sierra Nevada are famous.
47. At Berkeley, a graduate student never feels like a junior.
49. Location of notorious steps off seen on TV.
52. Swiss Sierra Nevada.
54. Berkeley initials of 1914.
56. Where the action is.
58. Where oral exams, graduate students hope not to ______.
60. Waterfall on an ancient time.
61. Waterfalls, lakes and granite hence, 4 hrs. east of Berkeley.
65. First word represented by initials of 28 Across.
68. The entering Berkeley grad student is all ______.
69. Component of cyclotron.
70. Adverb's word and dr. ch.
71. Prominent California politico.
73. Valley, lowest spot in US.
74. Mass.
75. Cause of pleasant Berkeley summer.
76. Ernest O. Lawrence first built one in Berkeley.
80. If you're not looking at the bow, you are looking ______.
83. Object of Berkeley chemical research.
84. Opposite of 41 Down.
85. Berkeley electrochemical engineers are concerned with this.
88. Principal product of valley just north of Bay Area.
89. Another West Coast state (abbr)
90. Where Berkeley students go to see Willie Mays.
93. Red.
94. Hippy home.
96. Whitney is the highest one; it's in California, too.
97. Theme of many a rally.
101. Noted San Francisco hill.
103. At Trader Vic's in San Fran.
104. Or Oakland you may have a ______-Tiki.
105. He endeavor not to make our oral exams a ______.
107. Shot in tennis, played year-round by faculty and students.
110. A student is never for very long after he comes to Berkeley.
112. Noted wine-producing area near Berkeley.
114. French plane of World War I.
115. French king.
117. ____ Galadad.

DOWN
1. Sequoia sempervirens is the largest.
2. Common verb.
3. Island in San Francisco Bay.
5. Thing to do in Berkeley chemical library.
6. Just write ERH here -- we couldn't think of anything.
7. Dutch air line.
14. Lane at 33 Across.
15. Source of gold.
18. Rush with purple flower, common in Sierra Nevada.
19. Potato.
21. Type of current.
22. A lake, gem of the Sierra.
24. What this is all about (initiahs).
25. Industrial recruiters pick up the ______.
27. Scholarly area stressed at Berkeley.
29. British queen of North Beach.
31. Type of record.
31. First letter of acronym of recent Berkeley movement.
32. It was found at Sutter's Mill.
33. After you come to Berkeley, your future is ______.
34. Modern art form.
35. Goal of grad studies at Berkeley (abbrev).
36. Type of food, music, etc.
42. Berkeley icon discovered from Qualifying Examination.
44. It intersects Ashbury.
45. _______ Berkeley.
46. Last two letters of pigment.
47. Scottish no.
48. _______ only in winter in Berkeley (French).
51. Initials of sea water conversion process, patents held by U.C.
53. All but the he would send you warmly.
54. Noted Berkeley faculty member.
55. State University (abbr)
57. When you go fishing in the Sierra, you bring your _______.
58. What old professor became.
59. French king.
60. Same as 33 Across.
61. Container for beer and ale at Laval's near campus.
62. Location of college.
63. Nature of Berkeley faculty.
64. Mr. Matchy.
65. Registered nurse.
66. University of California at Berkeley.
67. Length of typical midterm quiz.
70. Another result of 76 Across.
71. Type of flower.
72. Pope.
73. Berkeley's computer isn't IBM or HAI.
74. Substance of concern to chemical engineers.
75. Computer-tells sometimes count in.
77. Attending Berkeley starts you on the road to success.
80. Aeronaut who also flies snow and drives speed record from Qualifying Examination.
81. Element No. 93, discovered in 1913.
82. A study of art under research by Berkeley Chem. E's.
83. Family food.
84. Never regard the faculty as your ______.
85. Most classes are held in the _______. The California sun keeps one from looking out.
87. Greek letter.
88. Baghdad (Bay).
89. Conjunction.
90. Component of distillation column.
92. Curse you, baron!
93. Berkeley chemists found _______.
94. Popular musical, now playing in San Fran.
95. Our graduate students are all ______ scholars.
96. Hawaiian food.
UNIVERSITY OF CALIFORNIA, SANTA BARBARA

The Department of Chemical and Nuclear Engineering offers a full program of graduate courses and research projects leading to the M.S. and Ph.D. degrees in chemical engineering. Eight full-time faculty members direct research over a wide variety of chemical engineering and related nuclear engineering problems. Modern, well-equipped research laboratories and computer facilities (IBM 360/75) back up all research programs.

FACULTY

John E. Myers, Ph.D., Univ. of Michigan 1952. Professor of chemical engineering and chairman of Department. Research program: Two phase flow in porous media, mechanisms of boiling heat transfer.


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

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

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

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


CAMPUS

Santa Barbara is located on the Pacific coast one hundred miles north of Los Angeles. The campus occupies a 630-acre scenic promontory with the Santa Ynez mountains immediately behind. Twelve thousand students are enrolled in programs in diverse fields of engineering, science, humanities and the arts. Attractive housing of all kinds is available within walking distance of the campus.

FINANCIAL ASSISTANCE AND ADMISSION PROCEDURES

Teaching assistantships are available to qualified students; the stipend begins at $3,402 for the academic year with merit increases as progress is made towards a degree. A number of University Fellowships, Research Assistantships and various Traineeships are also available for qualified students. Information concerning departmental procedures can be obtained by writing Professor J. E. Myers, Department of Chemical and Nuclear Engineering, University of California, Santa Barbara 93106. Application forms for admission and financial assistance should be requested from the Dean of the Graduate Division, University of California, Santa Barbara 93106.
PROGRAM OF STUDY Distinctive features of study in chemical engineering at the California Institute of Technology are the creative research atmosphere in which the student finds himself and the strong emphasis on basic chemical, physical and mathematical disciplines in his program of study. In this way a student can properly prepare himself for a productive career of research, development, or teaching in a rapidly changing and expanding technological society.

A course of study is selected in consultation with one or more of the faculty listed below. Required courses are minimal. The Master of Science degree is normally completed in one academic year and a thesis is not required. The Ph.D. degree requires a minimum of three years subsequent to the B.S. degree, consisting of thesis research and further advanced study.

FINANCIAL ASSISTANCE Graduate students are supported by fellowship, research assistantship, or teaching assistantship appointments during both the academic year and the summer months. A student may carry a full load of graduate study and research in addition to any assigned assistantship duties.

APPLICATIONS Further information and an application form may be obtained by writing

Prof. C. J. Pings
Executive Officer for Chemical Engineering
California Institute of Technology
Pasadena, California 91109

It is advisable to submit applications before February 15, 1970.

FACULTY IN CHEMICAL ENGINEERING

WILLIAM H. CORCORAN, Professor and Vice President for Institute Relations
Ph.D. (1948), California Institute of Technology
Kinetics and catalysis; gas chromatography; plasma chemistry.

SHELDON K. FRIEDLANDER, Professor
Ph.D. (1954), University of Illinois
Aerosol physics; particle-surface interactions; interfacial transfer; diffusion and membrane transport.

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

CORNELIUS J. PINGS, Professor and Executive Officer
Ph.D. (1955), California Institute of Technology
Liquid state physics and chemistry; statistical mechanics.

BRUCE H. SAGE, Research Associate
Ph.D. (1984), California Institute of Technology
Eng.D (1958), New Mexico State College.

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

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

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

ROBERT W. VAUGHAN, Assistant Professor
Ph.D. (1967), University of Illinois
Solid state chemistry and physics, particularly effects of high pressure.
We are proud to announce that the National Science Foundation has awarded our department a Departmental Development Grant in the amount of $590,000. As a consequence we have available attractive Assistantships, Traineeships and Fellowships. For information on programs and stipends contact

Professor W. N. Gill, Chairman
Chemical Engineering Department
Clarkson College of Technology
Potsdam, N. Y. 13676

Please send further information on your graduate program to

Name ____________________________ Undergraduate School _______________________

Number and Street ____________________________________________________________

City ____________________________ State ______________ Zip Code ________________
DREXEL IS NOT AN AVERAGE SCHOOL

For example, Drexel awards more engineering degrees than any other private university.

PROGRAMS: M.S. and Ph.D. in Chemical Engineering.

RESEARCH:
- Drying Dynamics
- Atomization Phenomena
- Environmental Problems
- Biomedical Engineering
- Process Dynamics and Control
- Fluid Mechanics of Films
- Optimization of Drying Processes
- Catalysis of Reverse Flow Reactors

SUPPORT:
Fellowships, Research Assistantships, and Teaching Assistantships are awarded to qualified students. The minimum stipend is $275/month plus remission of tuition and fees.

LOCATION:
In Philadelphia, the hub of the industrialized Delaware Valley. Contact with many of the chemical and petroleum companies of the area is convenient and frequent.

For further details, please send this form to:
Dr. John A. Tallmadge, Graduate Advisor; or
Dr. Donald R. Coughanowr, Chairman
Department of Chemical Engineering

NAME: ____________________________
ADDRESS: ____________________________
SCHOOL: ____________________________
I AM INTERESTED IN: M.S. ___ Ph.D. ___
Full-Time ___ Part-Time ___
GRADUATE PROGRAMS IN SCIENCE AND SYSTEMS

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

CHEMICAL ENGINEERING SCIENCE
- Transport phenomena
- Thermodynamics
- Materials science
- Fluid dynamics
- Kinetics
- Applied Math

CHEMICAL ENGINEERING SYSTEMS
- Chemical reaction engineering
- Separations processes
- Computer aided design
- Process dynamics
- Process control
- Optimization

INTERDISCIPLINARY
- Energy conversion
- Biomedical
- Microelectronics
- Polymer science
- Process economics
- Bioengineering

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

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

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

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

In addition to facilities available in a new Chemical Engineering building, research is conducted in the Ames Laboratory, a National Laboratory of the US Atomic Energy Commission, located on the Iowa State campus. A staff of nearly 1,000 at the Laboratory conducts basic research of long-range interest to the nuclear industry.

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

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

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

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

Name__________________________ Undergraduate School___________________________

Number and Street___________________________

City___________________________ State_________ Zip Code_________
UNIVERSITY OF KENTUCKY

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

including

A Unique Program in AIR POLLUTION CONTROL

Kinetics and equilibria of atmospheric reactions
Micrometeorology
Diffusion in the atmosphere: modelling of urban areas
Air sampling and analysis
Process and system control; air cleaning
Effects of pollutants on man, materials, and environs

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

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

Contact: Robert B. Grieves
Dep't of Chemical Engineering
University of Kentucky
Lexington, Kentucky 40506
Department of Chemical Engineering

Program of Study
This department offers work leading to the Master of Science degree in chemical engineering and the Doctor of Philosophy degree in chemical engineering. The Master of Science degree may be earned under either thesis option or a course work option. Where practical, the thesis option is encouraged for students planning a terminal Master of Science. A Master of Science in sugar engineering is also available through the department.

Each of twenty graduate courses is taught at least once each academic year. Undergraduate preparation should normally be the equivalent of that established as the minimum requirement for accreditation by the Engineers' Council for Professional Development. Special cases will be considered by the Head of the Department.

The Master of Science degree requires a thesis plus 24 course work credit hours of which a minimum of 12 must be taken in chemical engineering. For nonthesis Master of Science students, 36 credit hours are required.

For the Ph.D. degree a minimum of 60 credit hours beyond the baccalaureate are required. These must include 18 to 27 credit hours in chemical engineering, 12 to 15 in one or two minor subjects, 3 to 6 in cultural electives, and 12 to 15 in technical electives. A maximum of 9 credit hours is allowed for dissertation research. In addition each candidate must demonstrate a reading knowledge in at least one foreign language.

Research Facilities
Within the Chemical Engineering Department are a number of special purpose research facilities which include a reacting fluids laboratory, thermal fluids laboratory, a high polymers laboratory and a modern computing laboratory which includes analog, digital and hybrid computers. The department is also serviced by such University facilities as the Nuclear Science Center, the Computer Research Center, and one of the most modern libraries in the South with holdings of more than 1,300,000 volumes.

Financial Aid
A number of fellowships and assistantships are available for graduate students during the academic year. Fellowship and research assistantship support is provided by the NSF, NDEA, HEW, NASA, DOD, the University, and private industry. Typical academic year stipends for half-time graduate assistantships or fellowships range between $2250 and $2700 (tax-free) plus an additional tuition and fee exemption (not including an activity fee of $55).

Graduate students have no difficulty in obtaining technical employment during the summer because of the local concentration of chemical and allied industry in the area. Alternatively, full-time summer research support is also possible.

Cost of Study
For each regular semester (up to 12 credit hours) graduate student tuition includes a general fee of $50, a University fee of $55, an activity fee of $55, and a nonresident fee (if applicable) of $100.

Cost of Living
For single students, dormitory rooms vary from $81 to $225 for men and $119 to $227 for women per semester. Unfurnished apartments for married students rent for $65 to $90 monthly. Many reasonably priced off-campus apartments and residences also are available for students within the University environs.

Student Body
Undergraduate enrollment on the Baton Rouge campus averages 14,800, 40 per cent of whom are women. Graduate and professional enrollment is over 3,500. Students are drawn from every state in the Union and more than 60 foreign countries. About 720 international students are registered each academic year in both the undergraduate and graduate programs.

Graduate enrollment within the Department of Chemical Engineering is approximately 90, including part-time and full-time students. There are 40 full-time graduate students, of whom 19 are doctoral candidates and 21 are master's or predoctoral candidates. Currently, 38 full-time graduate students in the department are receiving financial aid.

The Community
LSU, situated within the city of Baton Rouge, has the unique advantages of a growing metropolis of over a quarter of a million people as well as those of the outlying countryside, a paradise for fishing, boating, and hunting enthusiasts. In addition the University supports a vast cultural and recreational program in music, drama, art, and literature as well as fine programs in athletics. Just eighty miles southeast of the main campus, at the entrance to the Gulf of Mexico, is New Orleans, internationally known for its southern hospitality, charm and recreational activities.

The University
Louisiana State University and Agricultural and Mechanical College is a multicampus, multipurpose system of higher education, exerting a major influence on the economic, social, and cultural life of all its citizens. Founded as a land-grant institution in 1860, LSU has grown to become one of the leading universities in the South. The main campus consisting of 15 colleges and specialized schools is located on a beautifully landscaped 300-acre plateau just east of the Mississippi River. Although physically retaining the beauty of its southern heritage, the University is nevertheless a modern facility reflecting the scholarship and culture of the present.

Applying
Applications for admission, although considered throughout the year, should be made as early as possible. For those seeking financial assistance it should be made preferably by March 1 for a fall appointment and November 1 for the spring semester. The aptitude portion of the Graduate Record Examination is required for all applicants.

Correspondence and Information
Department of Chemical Engineering
Louisiana State University
University Station
Baton Rouge, Louisiana 70803
A CAREER IN THE PAPER INDUSTRY?

Manufacture of Pulp and Paper is one of the largest and fastest growing industries in the United States and the world. A research renaissance in product and process diversification provides exceptional growth opportunities for men and women in all disciplines of engineering and science. Such talents are in demand for research, industrial engineering, business management, marketing, systems planning—you name it, this industry offers it.

Train for it at the University of Maine

The Department of Chemical Engineering at the University of Maine, Orono, pioneered the first paper studies program in the United States, and continues to lead in teaching multidisciplinary application of engineering sciences to the varied and complex operational decisions of this forest resources industry. The modern and rapidly expanding paper industry of this state provides an exceptional opportunity for cooperative interaction of University based programs with real life problems of industrial development.

Students with a B.S. degree in most scientific or engineering disciplines can program a fifth year extension of their undergraduate curriculum to fulfill requirements for a Certificate of Advanced Study in Pulp and Paper Management. One half of the fifth year covers basic fiber science and the technology of pulp and paper production. The other half can be an elective sequence to develop special interests in:

COURSES
Systems Engineering
Environmental Engineering
Applied Computer Sciences
Polymer Science
... and others

Students who apply and qualify for admission to graduate school can fit a substantial part of their fifth year Certificate Program to graduate school requirements for a Master of Science degree in Pulp and Paper Technology, in Systems Engineering, or in Chemical Engineering.

GRANTS
The University of Maine Pulp and Paper Foundation offers grants to qualified students who undertake the fifth year program. Such grants of full tuition plus $1100 cover all essential academic costs. Fellowships and Assistantships are available also for a limited number of students beyond the fifth year who aim for a Ph.D. in Chemical Engineering.

FOR DETAILED INFORMATION
For more detailed information about the pulp and paper programs at the University of Maine and the financial assistance available write:

Dr. Edward G. Bobalek
Chemical Engineering Department
255 Aubert Hall
University of Maine
Orono, Maine 04473
THE UNIVERSITY OF MICHIGAN OFFERS

EXPERIENCE

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

VARIED RESEARCH

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

CULTURAL ENVIRONMENT

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

FINANCIAL ASSISTANCE

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

Write for information and a special book to:

Robert H. Kadlec, Chairman of the Graduate Committee
Department of Chemical and Metallurgical Engineering
The University of Michigan
Ann Arbor, Michigan 48104

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

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

**Nuclear Engineering**
- Nuclear Reactor Physics
- Nuclear Reactor Design
- Nuclear Reactor Operation
- Radiation Induced Reactions
- System Dynamics
- Radiation Shielding
- Radiation Engineering
- Thermonics

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

**Applied Polymer Science**
- Polymer Physics
- Graft Polymerization
- Polymerization Kinetics
- Non-Newtonian Flow

**Biological and Environmental Engineering**
- Aerosol Mechanics
- Membrane Separations
- Artificial Organs
- Bioengineering
- Environmental Health
- Air Pollution Control

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

**Address inquiries to**

Dean, Graduate School or Chairman Department of Chemical Engineering
Established fields of specialization in which research programs are in progress are:

1. Fluid Turbulence and Drag Reduction Studies—Drs. J. L. Zakin and G. K. Patterson
2. Electrochemistry and Fuel Cells—Dr. J. W. Johnson
3. Heat Transfer (Cryogenics) Dr. E. L. Park, Jr.
4. Mass Transfer Studies—Dr. R. M. Wellek
5. Structure and Properties of Polymers—Dr. K. G. Mayhan

In addition, research projects are being carried out in the following areas:

(a) Optimization of Chemical Systems—Dr. J. L. Gaddy
(b) Evaporation through non-Wettable Porous Membranes—Dr. M. E. Findley
(c) Multi-component Distillation Efficiencies—Dr. R. C. Waggoner
(d) Gas Permeability Studies—Dr. R. A. Primrose
(e) Separations by Electrodialysis Techniques—Dr. H. H. Grice
(f) Process Dynamics and Control—Drs. M. E. Findley, and R. C. Waggoner
(g) Transport Properties and Kinetics—Dr. O. K. Crosser

Tuition: Out of state tuition waived for Graduate Students. Fees are approximately $200 per semester for 10 credit hours or more.

Financial aid is obtainable in the form of Graduate and Research Assistantships, Industrial Fellowships and Federal Sponsored Programs. Aid is also obtainable through the Materials Research Center.
GRADUATE STUDY
IN
CHEMICAL ENGINEERING
AT THE
UNIVERSITY OF NEBRASKA

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

Biochemical Engineering
Computer Applications
Crystallization
Desalination
Food Processing
Heat Transfer
Kinetics

Laser Applications
Mass Transfer
Mixing
Polymerization
Thermodynamics
Ultrasonics
and other areas

FOR APPLICATIONS AND INFORMATION
ON AVAILABLE FINANCIAL ASSISTANCE

WRITE TO
Prof. J. H. Weber, Chairman
Department of Chemical Engineering
University of Nebraska
Lincoln, Nebraska 68508
THE CITY COLLEGE
OF
THE CITY UNIVERSITY OF NEW YORK
ANNOUNCES A SPECIAL PROGRAM IN

ENGINEERING APPLICATIONS OF PROBABILITY
THEORY

Engineers working in the areas of control, communications and reliability have long been familiar with stochastic processes and have contributed to the development of the theory. The powerful mathematical tools developed in these contexts, such as the Theory of Markov processes, Queueing and Renewal Theory, etc., have till recently found only limited application in the chemical engineering profession and many research engineers are still unfamiliar with its use. In the last few years these methods have gained wider acceptance and their usefulness has been demonstrated by different workers in a number of fields.

Our department is conducting one of the largest concentrated research efforts in this field. The research group is headed by Professors Stanley Katz and Reuel Shinnar and is active in a wide variety of problem areas endeavoring to demonstrate the usefulness and power of probability methods when applied to contemporary chemical engineering problems.

Emphasis is given both to extensions of the theory and the development of new methods, as well as to new applications of the methods developed in other fields. Areas of investigation include:

1) Mixing and turbulence in chemical reactors.
2) Control of process plants.
3) Theory of tracer experiments.
4) Applications of tracer experiments to physiological problems.
5) Behavior of particulate systems, with emphasis on crystallization, polymerization and more recently, meteorological problems.

The program is specially suited for students with a mathematical inclination, providing them an opportunity to enter a new and growing field in chemical engineering. Research assistantships for students intending to study for the doctoral degree as well as a few post-doctoral fellowships are available. Inquiries should be directed to

Professor A. X. Schmidt
Department of Chemical Engineering
The City College of the City University of New York
New York, N. Y. 10031
When you’ve got it . . .

- Oklahoma, a vigorous state with space to dream and grow, with a unique heritage and a promising future . . .
- a friendly city with a tradition of fine arts excellence and exceptional recreation opportunities . . .
- a University where human beings share values and concerns, where innovation and relevance are more than words . . .
- a balanced department oriented to its missions . . . quality teaching for graduate and undergraduate students . . . providing basic knowledge through research . . . translating that knowledge to practical use through public service . . .
- bright, young faculty members with energy and dedication, highly-motivated in teaching, research and public service, beginning to achieve deserved recognition . . .
- a curriculum that has produced outstanding doctor of philosophy recipients, 68 in the past 7 years, 17 of whom are in professorial positions . . .
- academic opportunity, intellectual challenge, and an atmosphere of creativity.

The School of Chemical Engineering and Materials Science
The University of Oklahoma
Norman, Oklahoma
GRADUATE STUDY IN CHEMICAL AND PETROLEUM ENGINEERING

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

PROGRAM

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

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

FINANCIAL ASSISTANCE

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

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

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

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

FACULTY AND FIELDS OF RESEARCH

IN CHEMICAL ENGINEERING

Dr. Charles S. Beroes
Gas Dynamics, Process Design & Optimization
Unsteady State Heat Transmission

Dr. Alan J. Brainard
Thermodynamics, Mass Transfer

Dr. George D. Byrne
Applied Mathematics

Dr. Shiao-Hung Chiang
Mass Transfer, Interfacial Phenomena

Dr. Morton Corn
Air Pollution

Dr. James Coull
Chemical Kinetics, Catalysis, Polymers

Dr. Benjamin Gal-Or
Thermogravitational Separation

Dr. Harold E. Hoelscher
Transport Phenomena, Thermodynamic Properties

Dr. George E. Klinzing
Relativistic Thermodynamics

Dr. Chung-Chiun Liu
Reaction Kinetics, Reaction Kinetics

Dr. Yatish T. Shah
Interfacial Phenomena

Dr. Edward B. Stuart
Transport Phenomena

Dr. John W. Tierney
Thermodynamics, Adsorption

Dr. Lemuel B. Wingard
Process Dynamics, Equilibrium Stage Calculations

IN PETROLEUM ENGINEERING

Dr. Paul F. Fulton
Multiphase Flow in Porous Media, Wettability

Prof. James H. Hartsock
Computer Applications to Unsteady State Flow

Dr. Joseph J. Taber
Interfacial and Surface Phenomena, Miscible Displacement

Available to qualified students.

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

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

Graduate Coordinator
Chemical and Petroleum Engineering Department
601 Engineering Hall
University of Pittsburgh
Pittsburgh, Pennsylvania 15213
Syracuse University is a private university situated among the hills of Central New York State. A broad cultural climate which stimulates interest in engineering, science, the social sciences, and the humanities exists at the university.

DEPARTMENT OF CHEMICAL ENGINEERING AND METALLURGY

Programs leading to Master's and Ph.D. Degrees in Chemical Engineering, Master's Degree in Metallurgy, and Master's and Ph.D. Degrees in Solid State Science.

GRADUATE CURRICULUM EMPHASES:

Computer Science  Mathematical Modeling  Separation Processes

INDEPENDENT STUDY AND RESEARCH PROBLEMS:

Water Renovation  Optimization of Multistage Processes
Rheology and Viscoelastic Fluid Phenomena
Membrane Processes  Biomedical Applications
Mechanical Behavior of Solids  Thermodynamics and Kinetics
Surface Science  Metal Physics  Electron Microscopy

FINANCIAL ASSISTANCE:

Graduate Fellowships and Assistantships. Stipends range from $2,000 to $5,000 with most students receiving $4,000 per annum in addition to remitted tuition privileges.

For Information Contact:

Dr. James A. Luker, Chairman
Department of Chemical Engineering and Metallurgy
Syracuse University
Syracuse, New York 13210
Telephone: Area 315—476-5541, extension 2559
AT THE UNIVERSITY OF TENNESSEE
GRADUATE STUDY IN CHEMICAL & METALLURGICAL ENGINEERING

PROGRAMS for the degrees of Master of Science and Doctor of Philosophy are offered in both chemical and metallurgical engineering. The Master’s program may be tailored as a terminal one with emphasis on systems and design, or it may serve as preparation for more advanced work leading to the Doctorate. Interests of the staff include thermodynamics, physical metallurgy, diffusional operations, heat transfer, fluid mechanics, polymer science, reaction kinetics, information operations, and systems analysis and design as applied to both chemical and metallurgical engineering.


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

FINANCIAL ASSISTANCE from a number of sources is available, including graduate assistantships, graduate teaching assistantships, research assistantships, industrial fellowships, industrial grants-in-aid, NSF Traineeships, NASA Traineeships, NDEA (Title IV) Fellowships, and University Non-Service Fellowships.

COST OF STUDY—Full-time students who are Tennessee residents pay $105 per quarter maintenance fee; out-of-state students pay an additional tuition of $205 per quarter. Holders of fellowships, graduate assistantships, and certain teaching appointments pay no fees or tuition.

COST OF LIVING—Dormitory rooms costs for single students range from $75 to $100 per quarter; combined room-and-board arrangements are available at $305 per quarter. Attractive one- and two-bedroom apartments for married students rent from $60 to $110 per month unfurnished, approximately $15 higher furnished. Privately operated apartments are available to single or married graduate students at equivalent and higher rates. Food and other living expenses are below national averages.

STUDENT BODY—About 16,000 undergraduate and 4,000 graduate students are enrolled at the Knoxville campus of the University of Tennessee. In the College of Engineering there are approximately 2200 undergraduate and 300 resident graduate students.

KNOXVILLE AND SURROUNDINGS—Knoxville, with a population near 200,000, is the trade and industrial center of East Tennessee; convenient transportation is available to all parts of the country. The University is located about five blocks from the downtown business area. In the nearby Auditorium-Coliseum, Broadway plays, musical and dramatic artists, and other entertainment events are regularly scheduled. Knoxville has a number of points of historical interest, a theater-in-the-round, an excellent symphony orchestra, two art galleries, and a number of museums. Within an hour’s drive are many TVA lakes and mountain streams for fishing, boating, and water sports; the Great Smoky Mountains National Park with the Gatlinburg tourist area; two state parks; and the atomic energy installations at Oak Ridge, including the Museum of Atomic Energy. A vast number of cultural, recreational, and social activities are available on the University campus.

A WORD ABOUT U.T.—Founded in 1794 as Blount College, The University of Tennessee has grown to a large multi-campus, multi-purpose system of higher education covering the entire state. Graduate programs in science and engineering centered at the Knoxville campus have developed to major size and strength over the past 25 years. A major stimulus to the growth of these programs has been the proximity of the atomic energy facilities at Oak Ridge and the close cooperation that has developed between these facilities and the University.
• Graduate degrees granted: Master of Science in Chemical Engineering
• Courses for graduate credit are available in the evenings.
• Typical research interests of the faculty include the areas of: mass transfer, particularly distillation and liquid-liquid extraction; thermodynamics; mathematical applications in chemical systems; reaction kinetics; process dynamics and control; metallurgy and the science of materials; nuclear engineering.
• Assistantships and scholarships are available.
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Barlage, W. B., Ph.D., N. C. State—Transfer Processes in Non-Newtonian Fluids
Beckwith, W. F., Ph.D., Iowa State—Transport Phenomena
Hall, J. W., Ph.D., U. Texas—Chemical Kinetics, Catalysis, Design
Harshman, R. C., Ph.D., Ohio State—Chemical and Biological Kinetics, Design
Littlejohn, C. E., Ph.D., V.P.I.—Mass Transfer
Melsheimer, S S., Ph.D., Tulane—Process Dynamics, Applied Mathematics
Mullins, J. C., Ph.D., Georgia Tech—Thermodynamics, Adsorption

FINANCIAL ASSISTANCE—Fellowships, Assistantships, Traineeships

Contact:
C. E. Littlejohn, Head
Department of Chemical Engineering
Clemson University
Clemson, S. C. 29631

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FOR FURTHER INFORMATION YOU ARE INVITED TO WRITE:

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

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For application and information, write to:
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Contact: Dr. T. W. Hoffman, Chairman
Dept. of Chemical Engineering
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FOR FURTHER INFORMATION ADDRESS:  
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M. S. Program in Chemical Reaction Engineering

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R. E. Wainerdi, Activation Analysis

For information concerning the graduate program contact
Dr. P. T. Eubank, Graduate Advisor, Texas A&M University, Department of Chemical Engineering, College Station, Texas 77843

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