GRADUATE EDUCATION ISSUE

PROCESS HEAT TRANSFER . . . . Bell
EQUILIBRIUM THEORY . Chao & Greenkorn
BIOLOGICAL TRANSPORT . . . . Cooney
MODELING . . . . . . . . . . . . Curl & Kadlec
SURFACE CHEMISTRY . . . . . Gainer
TRANSPORT PHENOMENA . . . . Slattery
DESIGN PROJECT . . . . Kelleher & Kafes
ENTREPRENEURSHIP . . . . Douglas & Kittrell

Graduate ChE at Loughborough . . . . FRESHWATER & LEES
A Plan for Graduate Student Research . . . . NEWMAN
Examining Trends in Grading . . . . . WHITWELL & LAPIDUS

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A LETTER TO CHEMICAL ENGINEERING SENIORS

As a senior you may be asking some questions about graduate school. In this issue CEE attempts to assist you in finding answers to them.

Should you go to graduate school?

Through the papers in this special graduate education issue, 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. 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 continuing the practice of featuring articles on graduate courses as they are taught by scholars at various universities. Previous issues included articles on applied mathematics, transport phenomena, reactor design, fluid dynamics, particulate systems, optimal control, diffusional operations, computer aided design, statistical analysis, catalysis and kinetics, thermodynamics and certain specialized areas such as air pollution, biomedical and biochemical engineering. We strongly suggest that you supplement your reading of this issue by also reading the articles published in previous years. If your department chairman or professors cannot supply you with the latter, we would be pleased to do so at no charge. But before you read the articles in these issues we wish to point out that (1) there is some variation in course content and course organization at different schools, (2) there are many areas of chemical engineering that we have not been able to cover, and (3) the professors who have written these articles are not the only authorities in these fields nor are their departments the only ones that emphasize that particular area of study.

What is the nature of chemical engineering graduate research?

One way in which you can obtain an answer to this question is to read papers in the technical publications; but another way you may obtain insight into graduate research is to learn something about the people who are outstanding chemical engineering scholars. To assist you in doing so we are again this year including an article on one of the “Founders of Chemical Engineering,” the late Professor B. F. Dodge of Yale University. Dr. Dodge has not only made numerous significant contributions to the literature, but he has also had an enormous impact on his students—many of whom are the unseen readers of his excellent pioneering thermodynamics text.

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 and each of these 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 to go into industry. 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. Then again 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 suggest that you explore the possibility of continuing your education in graduate school.

Sincerely,

RAY FAHLEN, Editor CEE
University of Florida
Gainesville, Florida

DEPARTMENT CHAIRMEN: See page 189.
EXAMINING TRENDS IN GRADING

Sir: In the period including May 1961 through May 1971, 173 students stood for the general examinations for the doctorate in chemical engineering at Princeton. During that period a number of minor procedural changes were made in the conduct of the examinations and a substantial number of changes were made in the faculty which formulated and graded these examinations. At the same time there appeared to be little change in number and quality of students applying for, and accepting admission to, the doctorate program. The numbers of foreign students had, however, increased appreciably.

Concern was expressed by some members of the faculty that the department was either grading or formulating the examinations progressively harder, or both. To test this hypothesis the grades were examined by an arbitrarily chosen empirical linear model containing as independent variables the date, based on zero time in May 1961 expressed in years, the years which a student had spent in residence before presenting himself for the examination, the fraction of foreign students in each group of common data and common experience, and an arbitrary index to indicate students who were taking the examination a second time, having failed on the first attempt. The number of students presenting themselves for each examination varied widely, from a minimum of one to a maximum of 13. It was always necessary therefore to use absolute grades since the numbers involved were insufficient for any normalized or otherwise adjusted curve.

The model chosen may be represented as

$$\hat{Y}(i) = \sum_{k=1}^{p+1} b(k) x(i k)$$

where

- $k = 1, 2, \ldots, (p + 1)$, where $p$ is the number of variables,
- $i = 1, 2, \ldots, N$ with $n(j)$ the number of replicates at any one point in factor space;
- $\frac{1}{f} s(j) = N$

where $N$ is the total number of experimental points (i.e., grades available),

- $x(ik) =$ the i-th value of variable $k$,
- $b(k) =$ the coefficient estimated by a standard least squares procedure, and
- $\hat{Y}(i) =$ the grade estimated by the model for the i-th student (i.e., the i-th value of the independent variable). Various powers of these variables and various interactions were included in the model, as indicated in Table I. The response was, of course, the numerical grade given. The results of this analysis are reported here in the hope that this sort of treatment may prove of interest to other departments who suspect similar or related problems.

The data were analyzed by a regression program reported by Daniel and Wood and available through SHARE or VIM. In order to minimize correlation between variables, the approximate average value of each variable was subtracted from each item of data. Thus the model was written in terms which were essentially deviations rather than the original variables. A number of passes were made to take advantage of the various features of this program. For example, as indicated in Table I, the second and third powers of time, the second power of experience, and the interaction of time and experience were included at various times to see whether their contributions to the sums of squares removed by the models contributed appreciably to improvement of the fit of the data by the empirical equation. The Mallows’ criterion (see Daniel and Wood, op. cit., pages 86-87) was used as an aid to judging the importance of these variables.

Two techniques were used to estimate whether any individual grade might not fit the general correlation or

** The numbers under which these programs are registered are: SHARE, No. 360D-13.6.008; VIM, No. G2-CAL-LINWOOD. Daniel C. and Wood, F.S., Fitting Equations to Data, Wiley Interscience, 1971.

CHEMICAL ENGINEERING EDUCATION
might have undue influence on the values of the coefficients estimated. One was an examination of the residuals, representative plots of which are shown in Figures 1 and 2. The highest and lowest points which seemed to fall off the normal line were omitted and the data rerun. No appreciable influence of these points was observed, and they were returned to the data deck. The other technique is an examination of the relative influence which any point might have in establishing the estimate of the b(k) for any variable x(k). Three suspicious points (each being an exceptionally high grade) were detected by this technique and are therefore not included in the final analysis.

TABLE II. Study of Grades on General Examinations for Last Ten Years

<table>
<thead>
<tr>
<th>Date is years from May 1961; DEVDAT is deviation from average for variable.</th>
<th>Exp'ce is years experience prior to first submission for exam.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEVEXP is as with DEVDAT DVD**2 and **3 are squares and cubes of DEVDAT Model is linear combination of variables retained.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ind. Var (I)</th>
<th>Name</th>
<th>Coef. B(I)</th>
<th>S. E. Coef.</th>
<th>T-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td>7.78096D 01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>DEVDAT</td>
<td>-1.33827D 0</td>
<td>2.17D-01</td>
<td>6.2</td>
</tr>
<tr>
<td>2</td>
<td>DEVEXP</td>
<td>-6.08825D 0</td>
<td>1.51D 00</td>
<td>4.0</td>
</tr>
<tr>
<td>3</td>
<td>DVD**2</td>
<td>-2.47099D-01</td>
<td>7.19D-02</td>
<td>3.4</td>
</tr>
</tbody>
</table>

| No. of observations | 170 |
| No. of Ind. Variables | 3 |
| F-Value | 16.6 |
| Residual Root Mean Square | 7.33415476 |
| Residual Mean Square | 53.78982609 |
| Residual Sum of Squares | 8292.1113141 |
| Total Sum of Squares | 11606.40677941 |

The summary of the regression data is given by the computer output reproduced in Table II. It will be noted that only three parameters were needed to provide the best fit but that only about 23 percent of the original variance is accounted for by the regression model (see $R^2 = 0.2307$).

The failure of the $R^2$ statistic to act as a discriminating criterion of success for regression models is, of course, well known. In this instance it is very misleading since there are many replicates whose sum of squares should be removed from the remainder after accounting for regression (marked RESIDUAL SUM OF SQUARES in Table II) in order to leave a sum of squares estimating the lack of fit. The program will not perform this calculation. It does have a technique of searching "nearest neighbors" and converging on a number which should relate closely to the square root of the replication (i.e., "error") variance. In this case 6.2 to 6.3 appears to be a reasonable approximation of this standard deviation, suggesting that the error variance should be 38 to 40. Calculated independently from the truly replicated values (i.e., grades taken at the same time by students with the same months in residence), the error variance is 47.04. The program thus implies that the empirical model provides an excellent fit. In the experience of one of the authors the Daniel-Wood program tends to underestimate error variance when true replicates are available. It is not possible to decide whether this underestimate is a characteristic of the method and equally true when no true replicates exist. It is certainly a helpful estimate to provide some indication of the adequacy of the model if no true replicates exist.

<table>
<thead>
<tr>
<th>Source of Variance</th>
<th>Sum of Squares</th>
<th>d.f.</th>
<th>Mean Square</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>11606.41</td>
<td>170</td>
<td></td>
</tr>
<tr>
<td>Due to regression</td>
<td>2677.30</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Total from regression</td>
<td>8292.11</td>
<td>166</td>
<td></td>
</tr>
<tr>
<td>* Due to replication</td>
<td>8089.81</td>
<td>130</td>
<td>46.85</td>
</tr>
<tr>
<td>Due to lack of fit</td>
<td>2839.30</td>
<td>36</td>
<td>78.87</td>
</tr>
</tbody>
</table>

$F(36,130) = 78.87/46.85 = 1.68$

$R^2$ after removing sum of squares due to replication

$= 1.0 - \frac{2839.3}{11606.4} = 0.757$

* Calculated independently

In the present case an exact technique for lack of fit can be applied, as shown in Table III; the sum of squares for replication ("error") is removed from those remaining from regression and the resulting sum of squares provides a mean square which can be tested by the usual techniques of analysis of variance for lack-of-fit. As noted in Table III, the F-statistic is in the 90-95 percent region for this distribution, indicating a 5-10 percent chance that the hypothesis of zero lack-of-fit is correct. While these odds are poor by absolute standards, they are excellent for purely empirical models.

From these calculations, a suitable model for the grades in the period in question is (Continued on page 193)
REMINISCENCES OF
BARNETT F. DODGE

CHARLES A. WALKER
Yale University
New Haven, Conn. 06520

The record of Barnett Fred Dodge's contributions to his profession is clearly evident from his extensive writings on chemical engineering research, education, and practice, and in the list of honors bestowed on him by his fellow chemical engineers and others. He rated the title of expert in chemical engineering thermodynamics (a field in which he wrote the book), the behavior of materials and chemical reactions at high pressures, industrial water pollution control, and cryogenic engineering, and published numerous articles on these subjects.

It would be easy to expand on his accomplishments in research, education, administration, and consulting, but these are all in the written record, and I would prefer to turn to a more personal picture of this man.

The primary characteristics which come to mind in thinking about Dr. Dodge are his integrity, a sense of fairness in dealing with others, his openness in personal dealings, and his incredible sense of organization of his own efforts and those of his university and professional societies. We who were privileged to work closely with him learned early in the game that he would always keep us informed as to how we stood with him, that he trusted us to do our best, that we were left to our own devices with only minimum guidance from him, and that his word was as binding as any contract ever written. We learned also that it was entirely possible to engage with him in high-spirited arguments and then go out to a pleasant lunch!

He taught many things other than Chemical Engineering and was particularly effective in demonstrating by his every action the supreme importance of integrity.

Putting all of this on a more personal basis, I remember well arriving at Yale some thirty years ago and “taking” Professor Dodge’s graduate course in thermodynamics. I expected a lot because of his reputation. At first it was very puzzling. What kind of teaching was this that
didn’t involve polished lectures by the great authority? I must admit that during those first few weeks I sometimes wondered how he developed his reputation. Then I began to notice some things: the thought that had gone into preparing the problems, his mastery of the subject matter, the clarity of his thought in answering questions and in outlining new topics and concepts, and his sense of fairness and integrity. By the end of six weeks it was apparent that Dr. Dodge’s teaching method consisted of creating a superb atmosphere for learning. He was equally effective in all of his teaching, whether the subject matter was thermodynamics or process design or high-pressure research. (Incidentally, I recently had occasion to survey the accumulation of materials in his office and began to understand his success. Many notebooks of problem solutions were there, some for use in classes and many which he had apparently solved just to be sure he was keeping up with his field).

He taught many things other than chemical engineering and was particularly effective in demonstrating by his every action the supreme importance of integrity. In dealing with graduate students and colleagues he also taught us that we would get better responses in all that

### PROFESSOR DODGE

Professor Dodge was named Dean of the School of Engineering in 1960, and oversaw the conversion of the School into Yale’s current Department of Engineering and Applied Science, an integral part of Yale’s graduate and undergraduate curricula, the following year.

He was born in Akron, Ohio, on November 29, 1895. He earned his BS degree in chemical engineering from the Massachusetts Institute of Technology in 1917, and a Doctor of Science degree at Harvard University in 1925. Before enrolling at Harvard in 1922, he worked for three years for E. I. duPont deNemours & Co., chiefly on explosives, and for two years for the Lewis Recovery Corporation of Boston. From 1921-25 he held lectureships in chemical engineering at Harvard and Worcester Polytechnic Institute. He was appointed to the Yale faculty in 1925 as Assistant Professor, promoted to Associate Professor in 1930, and to full Professor in 1935.

During World War II he was an official investigator for the National Defense Research Council, and helped develop portable oxygen generators for the Navy. He also spent a year on leave from Yale with the Fercleve Corporation working on the Manhattan Project at Oak Ridge, Tenn. There he directed all experimental investigations and plant control work on the separation of uranium isotopes.

During his professional career, Prof. Dodge served as a consultant to many companies and agencies, among them the Oxygen Process Corporation of New England, the Connecticut State Water Commission, the Tennessee Valley Authority, the Phillips Petroleum Company, duPont, the H. K. Ferguson Company, Oneida, Ltd., and Brookhaven National Laboratory.

He was a member of the firm of Dodge, Bliss and Walker, consultants on the treatment of factory wastes, since 1951, and had been an editor of Chemical Engineering Science.

As early as 1930, Professor Dodge had devised several means of controlling pollution for the Connecticut State Water Commission, but there was little interest in the processes at the time and his ideas were not implemented. Until his death he was still active in the study of industrial waste control.

He also was widely known as a lecturer both in the United States and abroad. He had spoken in France under Fulbright grants at the University of Toulouse, the University of Lille and the Catholic University of Lille, and in Spain at the University of Barcelona, also under State Department sponsorship. These trips gave him an opportunity to exercise his linguistic ability: in France, he lectured in French, and in Spain, in Spanish.

In 1951 he traveled to Japan as a member of an engineering mission sponsored by the American Society for Engineering Education, and he also was invited several times to the Universidad Central de Venezuela in Caracas.

In 1960 he was a National Sigma Xi Lecturer speaking at colleges and universities in the Midwest and West, and in 1963, Reilly Lecturer at the University of Notre Dame.

Professor Dodge received numerous professional honors besides the Founders Award, the most recent being the Warren K. Lewis Award of the American Institute of Chemical Engineers in 1963. He was elected as the first recipient of the award for his work as an educator and researcher over the past 40 years.

He received the Walker Award of the AIChE in 1950 for his contributions to chemical engineering literature, and was honored as “Man of the Month” by Chemical Engineering magazine in its February, 1954, issue.

He was elected vice-president of the AIChE in 1954, and president in 1955. He was elected a Fellow of the American Academy of Arts and Sciences in 1960, and served as chairman of the Academy’s Engineering Committee from 1960-61. He received honorary degrees from Worcester Polytechnic Institute, the University of Toulouse, and the U. Central de Venezuela, Caracas.
He forced his students to think deeply . . . and he expected them to assume a considerable part of the responsibility for their own education.

we did if we approached him not simply with a problem but with a problem and our own ideas as to a solution. Then we had his complete attention and benefited from his helpful comments on our proposed solutions. He was a tolerant man in most respects and was willing to accept limitations of ability, but he was not tolerant of laziness or lack of responsibility.

What else did he do? He pursued a number of hobbies with almost the same intensity and pleasure as were exhibited in his professional work. For one thing, he was a fine photographer, one of those rare people whose color slides and home movies were delights to see. He worked hard at this, and I recall that he once wrote for his own benefit a paper summarizing methods of color photography. During all of his adult life he played tennis (well), swam (capably), and climbed mountains (seriously) all over the world. At age 55 or so he added skiing and ice-skating and became quite proficient at both. There were rumors that he planned to take up golf when he reached age 80, but, alas, this was not to be.

Dr. Dodge “retired” in 1964, but the only change in his habits which we were able to detect was in his office hours. For years they had been 8 AM to 5:30 PM, Monday through Saturday. In retirement they changed to 8:15 AM to 5:30 PM, Monday through Saturday. Among other accomplishments during these retirement years he wrote a book on cryogenic engineering which is now in manuscript form.

Dr. Dodge’s widow, Constance Woodbury Dodge, will be known to many chemical engineers who have met her and to others who know from the dedication in his book on thermodynamics, that she is a novelist “who writes more exciting books”. Together they created a warm atmosphere in the department, and many former graduate students here will have pleasant memories of Thanksgiving at the Dodge’s, where the only thing to avoid was being matched against either of them in ping-pong. She has kindly given his technical library to Yale and has authorized the placing of the contents of his office in the archives at Yale. He is also survived by a daughter, Phyllis Dodge Putney, and a son, Richard W. Dodge.

WOMEN ENGINEERS

BOZEMAN, MONTANA — Montana State University will set a record in 1972 in the production of girl chemical engineers. The six girls being graduated there are the largest number of female chemical engineers turned out by any U.S. university in a single year. Included in the group are, from the left, Margaret Striebel of Deer Lodge who is going with Mobil Oil Corporation at Ferndale, Wash.; Lara Larson of Sheridan, going to graduate school at Montana State; Lynn Sherick of Sidney who is married to a philosophy student and who expect a tour of duty with the Peace Corps this summer; Mildred Liknes of Great Falls who is going to Norway for the summer before locating in the petroleum or paper industry of the Pacific Northwest; Sandra Punke of Missoula, going to the West Coast petroleum industry; and Ann Berg of Bozeman who is going to graduate school at Montana State.

NEW EDUCATION SESSION

AIChE NEW YORK MEETING — To stimulate innovation in education the Education Projects and the Undergraduate Education Committees of the AIChE are sponsoring a unique experience at the November 26 to 30 meeting in New York.

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A Course in

PROCESS HEAT TRANSFER:
“Sufficient Conclusions From Insufficient Premises”

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GRADUATE EDUCATION in chemical engineering is overwhelmingly oriented towards preparing the student for a career in research. Yet a substantial majority - 80 per cent for an arguable estimate - of the total professional careers of chemical engineers with M.S. and Ph.D. degrees will not be in research. And, to anticipate a later point, it is conceivable that even a Ph.D. chemical engineer who spends his entire career in research or teaching would benefit from an occasional abrasive contact with that part of the world that he is trying to improve upon.

Recognizing and accepting the above statements as having some useful implications for graduate education, the chemical engineering faculty at Oklahoma State University has always emphasized in both course work and research the application of fundamental principles to the several aspects of chemical engineering practice. We have also emphasized the role of problems arising in practice in pointing out the most profitable areas in which to conduct research.

Further, we have found it vital to at least introduce the graduate student to the philosophy and technique of solving those engineering problems which must be solved and for which available theory tells us little more than what cannot be done. A majority of real problems falls in this category, and I submit that it is the failure to recognize and admit this fact that accounts for much of the estrangement between academia and industry.

For the long run, one basically optimistic point of view holds that research is catching up — that more and more fundamental understanding is available to underpin our solutions, and that we may witness the day when real problems may be quantitatively solved in their essentials by the rigorous application of comprehensive mathematical statements of the physical and chemical processes involved, subject to socio-economic constraints and objective functions. Another point of view argues that our technological problems are growing in several dimensions more rapidly than our theories and that the role of pragmatism is expanding. There are other kinetic models of engineering knowledge that may be put forth, but the common lesson of all is that chemical engineers practicing in industry in the foreseeable future must be proficient in knowing how to solve problems that are not well-set mathematically and indeed may be only poorly comprehended on any level. The operational imperative is that the problems must be solved; the engineer cannot be too nice about the means.

One such attempt to construct and teach a course emphasizing the solution of real, full-scale problems within this context is described here. It is not the only course so conceived and so dedicated either at Oklahoma State or elsewhere, but it does have certain possibly unique features that are worthy of consideration if not emulation.

THE COURSE IS Process Heat Transfer, a 3-credit hour course taught in three lectures per week for 15 weeks to all M.S. and M.Ch.E. (professional program) students in chemical engineering at Oklahoma State. Some undergraduate students and graduate students in other departments elect the course and it is available to employed engineers in a number of cities in Oklahoma via talk-back TV (more about that later). Prerequisites are the usual undergraduate courses in fluid mechanics, heat transfer, and thermodynamics; a process design course and a graduate course in transport theory are considered very desirable. Chemical engineering students have all of these courses; those from other fields will generally lack the latter two. In that case, particular care must be taken to provide more detailed explanations and outside references. Industrial experience is extremely valuable.

On completion of this course, the student should be able to:

“Life is the art of drawing sufficient conclusions from insufficient premises.” — Samuel Butler, Notebooks
Kenneth J. Bell received his BSChE at Case Institute of Technology and his MChE and PhD degrees at the University of Delaware, where he was a graduate assistant to the late Professor Allan Colburn. He joined Oklahoma State University in 1961 after working for General Electric and teaching at Case. He is a consultant to Phillips Petroleum Co. and Heat Transfer Research, Inc., and was associated with D. Q. Kern until the latter’s death in 1971.

Find, evaluate, and use fluid dynamic and heat transfer analytical solutions, empirical correlations, and data to predict pressure drop and heat transfer coefficients in component geometries during single phase flow, boiling and condensation.

Select a feasible and efficient heat exchanger configuration (involving both single and multiple units) to meet a given process application, using estimation techniques to quickly obtain approximate sizes.

Use published design procedures for rating standard exchanger configurations.

From available correlations, develop design methods for new exchanger configurations or new process heat transfer problems.

Analyze laboratory and plant exchanger data in order to develop new correlations or to troubleshoot plant problems.

One objective that cannot be described in the precise form demanded by the educational theorists is the development of an intuitive comprehension for what is important about a problem—less delicately put, a gut feeling for what real fluids will do in equipment of real metal built and operated by real people.

The topic list of the course is as follows:

I. Introductory Concepts
   - Conduction: one-dimension, steady-state
   - Film and overall heat transfer coefficients
   - The basic design equation
   - LMTD and configuration correction factors
   - NTU - ε method
   - Single phase flow inside tubes
   - Single phase flow across tube banks
   - Criteria for heat exchanger selection
   - General types of heat exchangers

II. Single Phase Heat Exchangers

Design of double pipe exchangers
Construction features of shell and tube exchangers
Selection of shell and tube exchangers
Analysis of shell side heat transfer and pressure drop
Special shell-side problems

III. Condensation and Condenser Design
   - Two-phase flow
   - Filmwise condensation
   - Desuperheating and subcooling in condensers
   - Condensation with non-condensables
   - Approximate method for multicomponent/partial condensers
   - Analysis of multipass and crossflow condensers
   - Dropwise condensation
   - Direct contact condensation

IV. Vaporization and Reboiler Design
   - Pool boiling
   - Reboiler configurations
   - Kettle reboiler design: narrow boiling range
   - Kettle reboiler design: wide boiling range
   - Thermosiphon reboiler design

V. Air-cooled Heat Exchangers
   - Extended surface; fin efficiency
   - Finned tube banks: friction factor and heat transfer correlations
   - Design of air-cooled equipment

VI. Mechanically-aided Heat Transfer
   - Mechanically-aided heat transfer equipment
   - Heat transfer in agitated vessels
   - Close-clearance heat exchangers
   - Mean temperature differences in mechanically-aided equipment

VII. Other Heat Transfer Equipment

The course emphasis is on equipment: selecting and designing it in the first place, troubleshooting it, modifying it for a new service, or making it operate within the inherent uncertainties and instabilities of process systems. It follows that the student needs to learn about the construction of heat exchangers in sufficient detail that he can visualize the problems of their construction, installation, operation, and maintenance.

Particular attention is paid to the visualization of the physical processes occurring inside heat exchangers, especially flow patterns. Anticipation of the interrelationship between the structure of the heat exchanger, the operating conditions, and the flow mechanisms (real, not idealized for the sake of analysis) is basic to selecting valid heat transfer coefficient correlations and evaluating the basic design equation, and to calculating the local and total pressure effects in the exchanger.

The student is given realistic design problems and is expected to come up with practical designs. The design methods presented in class are feasible for hand calculation (through Fair’s method for thermosiphons strains that idea to its limits).
Computer design methods exist for most of the equipment considered and the student is made aware of their existence and, in one or two example cases, their fundamental basis and logical structure. But it is only by cranking through the sequence of preliminary design estimate, rating, design modification, relaxation of constraints, etc., that the student comes both to understand the interplay of the many variables in the design and to appreciate the design philosophy. Once the student develops some competence and flair in making the engine go, he can add the bells, gongs, and whistles that come with a computer.

THE STUDENT IS encouraged to do rapid, back-of-the-envelope calculations to come up with preliminary designs in some detail. Not only are these calculations necessary to get started on a more rigorous design procedure, but they serve to keep the student's attention on the critical factors in a problem, rather than upon the details. Also, for many purposes, the preliminary designs thus obtained are quite sufficient. With a little practice, most students are able to estimate designs to within the limits of uncertainty in the basic operational data and design correlations for many run-of-the-mill applications.

The fact of uncertainty and the design consequences thereof are emphasized. Uncertainty in the basic correlations, in the way the correlations are assembled in the design method, in the physical properties and flow rates and compositions of the process streams, in the fouling characteristics, seasonal variations in the service streams, long-term changes in plant product composition and rate and in operating philosophy — all of these have design implications that the student should keep in mind while making his calculations. On the one hand, for example, this will keep him from making excessively precise calculations of one film coefficient when the other coefficient — or the fouling — is controlling. However, the other side of the same coin is that the student is expected to take some care in calculating the controlling coefficient, and in estimating and allowing for its inherent uncertainty, or to choose a design where fouling is minimized or can be controlled. The student is always expected to ask himself, "How wrong can I be? What are the consequences of being wrong? What can I do about it in the design?"

Optimization, in the sense in which most current literature deals with the subject, gets short shrift. Apart from ignoring the uncertainty alluded to above, the usual heat exchanger optimization procedure misses the boat by choosing the wrong objective function (usually something to do with the cost of the heat exchanger) and failing to consider operational problems. In another sense, however, the whole course deals with optimization using an objective function having to do with the cost of the product. This almost always means that the heat exchange system (not just the individual units) is designed so that it will achieve the specified changes in the thermal condition of the process stream over the entire operating cycle of the plant between turnarounds and do this with a minimum amount of attention. Avoiding a couple of days' lost production per year may completely outweigh the cost of over-surfacing or duplicating a critical exchanger.

Thus, in a mild fouling situation, the student may select a single large heat exchanger for a given service, designing it to operate satisfactorily over the entire cycle; in a more severe fouling case, he may select two smaller heat exchangers piped so that one may be cleaned while plant operation is modified to permit the other exchanger to hold the load; in a critical fouling case, he will specify two large exchangers, i.e., full standby capability. Some day, the whole task of optimizing a plant design in this sense may be taken over by computer — just as soon as one of our more creative computer manufacturers develops a randomly accessible crystal ball in core.

More attention is devoted to the correct analysis of the temperature difference than is customary in textbook or even design-manual discussions of heat exchanger design. It is quite easy in process problems to specify terminal temperatures and exchanger configurations that result in a zero true mean temperature difference, whereas no one has yet managed to reduce a heat transfer coefficient to zero. The basic design equation,

$$A_o = \int_0^{Q_T} \frac{dQ}{U_o(T-t)}$$

(where $A_o$ is the heat transfer area required, $Q$ the heat transferred, $U_o$ the local value of the overall heat transfer coefficient, $T$ and $t$ the local temperatures of the hot and cold streams respectively) is introduced at the beginning. Only later...
— and only after a complete exposition and careful examination of the assumptions and their range of validity — is the idea of a mean temperature difference (MTD) formulation of the design equation presented.

I am something of a fanatic on the “Zeroth Assumption” in the LMTD derivation: “All elements of a given stream in a heat exchanger have identical thermal histories.” Specifically, this means that the MTD concept cannot be simply applied to any heat exchanger with bypassing or internal leakage, which in turn means that almost all of the heat exchanger data in the literature and the correlations developed therefrom are of questionable validity and little generality. Laying this on the class in about the third lecture is roughly equivalent to using a 2 x 4 to get their attention. Some never quite recover their faith in anything (which is at least a step in the right direction); most begin to show signs of thinking about their assumptions simultaneously with working through a design procedure.

AS WITH ANY course, there is the question of a textbook. There is none available. The only book that comes close to having a suitable approach and objective is Kern’s “Process Heat Transfer,” and the students are encouraged to read in Kern to see a Grand Master at work. Unfortunately, this book is over 20 years old, there is hardly a correlation or a design procedure in the book that hasn’t been improved upon in the interim, and there is no hint of the possible role of the computer. So I wind up using notes that I have prepared and that I have cadged from others, notably Al Mueller of du Pont, Jerry Taborek and Joe Palen of HTRI, and Bill Small of Phillips. (Proprietary material is not used, but knowing what is in the proprietary material keeps one from saying a lot of things that are not true). The notes suffer from being uneven, incomplete, and often insufficiently detailed for use apart from the lecture material. From time to time, some of us talk about writing a textbook; something may come of it yet.

This is obviously a highly personal course, one closely tailored to my interests and experience. Citing Samuel Butler again: “Every man’s work, whether it be literature or music or pictures or architecture or anything else, is always a portrait of himself.” I regard this as a very positive attribute: one of the advantages of using a live classroom teacher or lecturer in preference to or in addition to books, tapes, etc., is the opportunity of watching him in action—confronting a problem, discussing the circumstances surrounding it, seeking a solution, pointing out Scylla and Charybdis, and perhaps at the end being able to say, “We tried it and it worked.”

I wish to avoid undue emphasis upon how unique in detail this course may or may not be. And I am not suggesting that every graduate student should be highly skilled in process heat transfer or any other particular body of engineering effort.

I do want to emphasize that there should be in every engineering student’s academic career one or more courses presenting the philosophy and technique of solving real problems, warts and all. This is the art of engineering. This is the end to which all else of the academic curriculum and engineering research is directed. I would like to think that every engineering faculty member was capable of teaching one such course.

ADDENDUM ON TV TEACHING

In the spring of 1972, this course was taught on closed-circuit talk-back television for the first time. There is a state-wide TV system in Oklahoma that links the three major universities (Tulsa, Oklahoma, Oklahoma State) and the major industrial centers. TV courses may be taken for full graduate credit; homework assignments and solutions are transmitted by a daily courier; examinations are proctored at the receiving end and then returned by courier.

The on-campus students are in the TV studio, so the lecturer does have a live audience in front of him. There are two cameras, one in the back of the studio, the other vertically above the lecturer’s note pad. The back camera can be focused on anything from the blackboard (green) running the width of the studio to just the lecturer’s face; the vertical camera can also yield excellent close-ups of small objects held in the hand. Both cameras are always on and an operator in the control room at the back of the studio selects which image is to be transmitted to the remote viewers on the system and to the two TV sets in the studio.

(Continued on page 170)
Equilibrium Theory of Fluids is one of the beginning courses we offer the new graduate students in the Fall Semester. The course is an evolution of thermodynamics which has been in more or less the same position in the graduate curriculum for many years at Purdue. We changed the name of the course a few years ago to reflect its changed emphasis and contents.

The objective of this course is the study of the equilibrium properties of gases and liquids that are of interest in chemical process calculations. The properties are defined and interrelated in the context of classical thermodynamics. The interpretation, correlation, and prediction of properties are made by appealing to molecular considerations. A coincident objective of the course is to impart training in classical and statistical thermodynamics. The usefulness of the training should go beyond the understanding of equilibrium properties.

The contents of the course belong in three broad areas: 1. Principles of thermodynamics and statistical mechanics, 2. Properties of homogeneous fluid phases, and 3. Phase and chemical equilibria. The progression of the course coincides with the above sequence so that the semester starts with the basic principles and ends up at the frontier of current engineering literature. Table 1 shows the breakdown of the course contents in parts and sections.

PART 1 CONTAINS a concise presentation of the fundamental concepts and laws of thermodynamics. These are shown to lead to criteria of physico-chemical equilibria, and to functions that are useful for the description of physico-chemical processes. The concept of equilibrium in physico-chemical systems is inherently more abstract than that in many other types of systems such as the mechanical or electrical. But it is central to chemical process systems. We therefore think it worthwhile to go through a development starting from scratch. (We are aware of the risk of repeating a substantial part of undergraduate material.

Hence, we depend on the use of hand-outs to keep lecturing to a minimum.)

The first section of Part 1 is in the nature of definitions. A discussion is then made of exact and inexact differentials. Thermodynamic laws are presented on the basis of this discussion regarding state functions. The zeroth, first, and second laws are stated in terms of the state function introduced — temperature, internal energy, and entropy respectively.

The usefulness of the thermodynamic laws is greatly extended with the introduction of the energy functions. The concept of their association with certain natural variables is basic to this usefulness. Since these functions are related to the reversible shaft work under various conditions of constraint they provide the point of departure for the development of criteria of equilibrium and stability of physico-chemical systems.

IN PART 2 WE RELATE the equilibrium properties of matter in bulk to the properties of the constituent molecules. Our main concern is to develop the formalism and to present a set of useful formulas. These are illustrated extensively with examples drawn from simple systems.

A dual function is served in relating the thermodynamic properties to the molecular properties: (1) a deeper understanding is gained of thermodynamics as the manifestations of large collections of particles. (2) the molecular viewpoint provides the basis for the interpretation, correlation, and prediction of properties.

We begin Part 2 with a discussion of the meaning of the micro and macro states. The micro function (for isolated systems), the canonical partition function (for closed systems), and the grand partition function (for open systems) are introduced for the representation of the system. When the statistical averages are evaluated the thermodynamic properties become expressed in terms of the partition functions. The equivalence of the partition functions is demonstrated.
Equilibrium properties of fluids are conveniently considered as made up of contributions due to the motion of the isolated molecules, and the cooperative motion of the molecules in interaction. The former make up the ideal gas properties and the latter determine the deviations from ideal gas behavior. Since we are interested in real fluids, we discuss intermolecular forces in Section 4. We then separate in Section 5 the thermodynamic properties due to intermolecular forces and express them in terms of configurational integrals.

All the example systems studied in Part 2 are simple and elementary, such as non-interacting particles, Einstein's crystal, one-dimensional lattice solutions, etc. Nevertheless they serve more than purposes of illustration. The simple results become useful when recombined and developed for the description of real fluids of considerable complexity. We might compare these possibilities to the mechanical engineer's tinkering with simple links and bars, for out of these are made complex machines.
In Part 3 we study the properties of gases and their mixtures. The properties can be clearly classified into two categories: the energy functions of the entire fluid, and the chemical-potential related functions of the components in the fluid. The first type of properties are of general interest to many disciplines. The second type of properties fall within the special interest of the chemical engineer.

The energy functions are needed for the determination of heat and work quantities that are associated with processes. Heat is always an important concern with any fluids. The mechanical work of compression and expansion can also be an important consideration in the processing of gas. This consideration sets the gases apart from the condensed phases for which compressibility effects are usually of secondary importance.

The chemical-potential-related functions (\(\mu, f\), fugacity, activity, etc) are the partial properties needed for the calculation of phase and chemical equilibria. Other partial properties, such as \(H_I\) and \(V_I\), are of interest mainly in so far as they reflect the effect on equilibrium due to changes of conditions.

Thermodynamic properties of gases are discussed in terms of their differences from their ideal gas values. We do not belabor the ideal gas values. Instead, we depend on the extensive tabulations of such properties in the literature. We are therefore free from considerations of the isolated molecules and their modes of internal motion which are adequately described in physical chemistry. Here we concentrate on the effects of intermolecular forces which determine real fluid behavior in contrast to that of the ideal gas.

The principle of corresponding states is the single most important tool for the general description of properties of fluids. Accordingly we emphasize generalized correlations (tabular and graphical) and generalized equations of state expressed in dimensionless reduced forms. For the treatment of gases, the reduced variables are formed with the critical properties. With the aid of correlations of the criticals with molecular structure, it becomes possible to make quantitative calculations for diverse substances from no more information than their structural formulas, if that should be the only piece of information available.

We include liquids in this Part where it is feasible to treat them as an extension of the gas phase. It is well known that a liquid partakes of the properties of both a gas and a solid to varying degrees depending on its state relative to the critical point and the triple point. Part 4 will be concerned entirely with liquids but from a different viewpoint.

The first six sections of this Part deal with pure gases. After an introductory discussion of the general qualitative features of the properties of fluids, we develop the formalism of their quantitative analysis in two ways: with \((T,p)\) and with \((T,V)\) respectively as the independent variables. With generalized correlations, and tabular and graphical data the set \((T,p)\) serves well. The necessary development is adequately covered in most texts. However, a corresponding development is usually lacking with \((T,V)\) as the independent variables. These are required in equations of state calculations with the electronic computer and are of increasing importance as the use of computers is increased. We therefore go to some length to present the general working formulas, and to show their use with example equations of state.

In the second part of the Part starting with 3.7 we discuss gas mixtures. The limiting behavior of low pressure gas mixtures is always completely determined by the pure component properties. From there on the formalism relating the energy functions of real gas mixtures to their low pressure limits remain the same as for pure gases.

With mixtures, however, there is the additional task of evaluating the partial properties, including the chemical-potential and related functions in equilibrium calculations. Even though it is possible in principle to do so with the generalized correlations, the calculations are too tedious to be practical. As a result equations of state assume added significance when applied to mixtures, for the equations are far more suited for computer applications.

In Part 4 we study liquids and their solutions. Liquids are probably the most common and least understood state of matter that occur in chemical processes. However, a systematic understanding of their behavior is basic to the rational design of separation operations involving liquids such as distillation, crystallization, extraction, and so on.

A liquid shares the properties of gases and solids to varying extents depending on the relative
A dual function is served in relating the thermodynamic properties to the molecular properties — a deeper understanding is gained of thermodynamics as the manifestations of large collections of particles and the molecular viewpoint provides the basis for the interpretation, correlation, and prediction of properties.

proximity of its state to the critical point and the triple point. Our main interest in Part 4 is about liquids at states far removed from the critical. Liquid states close to the critical were part of the discussion of the preceding Part. In the introductory part of Part 4 we present a general molecular view of liquids. Reflecting recent progress, the cell theory is developed into useful generalizations of the properties of non-polar liquids, including simple molecules, and chain molecules. We then discuss properties of pure liquids that will be needed in subsequent studies of liquid solutions.

The remainder of Part 4 concerns solutions. In §3 to §5 we present the formal framework for the description of solution properties on the basis of classical thermodynamics. Then, starting with §6 we discuss the various procedures for the quantitative interpretation, correlation, and prediction of non-ideal behavior of solutions.

The molecular viewpoint provides us with a most useful classification of liquid solutions. Our quantitative description of their non-ideal behavior is based on the same classification. Thus in §7 we describe nearly-ideal systems in which the molecules are highly similar. A linear perturbation theory adequately describes their non-ideality. This theory applies to almost all superfractionation systems as well as a number of other close-boiling mixture systems of exceptional importance such as propane/propane.

From there on we proceed to systems showing progressively larger non-ideality. We describe solutions of non-polar molecules of appreciably different interaction energies in §8, and of appreciably different sizes in §9. The procedures provide useful descriptions of hydrocarbon mixtures.

The highly non-ideal behavior of solutions containing polar molecules is the basis of azeotropic and extractive distillations. A simple example would be the relative volatility of methanol to ethanol which can be controlled by adding water so that either methanol or ethanol can be distilled as the overhead product. All liquid-liquid extraction processes similarly depend on the utilization of non-ideal solution behavior. Such highly non-ideal solution systems individually required specific and extensive experimental studies until relatively recent times. Then investigations along the lines of group contributions began to bear fruit, until today many general results have been obtained for the description of chain molecules with attached polar groups. We describe this development in §10 to conclude Part 4.

**In the Last Two Parts** of this course, Parts 5 and 6, the materials of the first four Parts are applied to the study of phase and chemical equilibria. Relatively few new principles are introduced here, but the applications serve as an effective review of the preceding materials, as well as to make more sense of them.

In summary, Equilibrium Theory of Fluids hopefully gives the students:

1. A systematic understanding of the equilibrium properties of fluids that are needed in the analysis of chemical processes, with some appreciation of what is critically important and where, and what is not so critical.
2. Some experience in the application of physico-chemical principles to industrial problems.
3. Reinforced training in thermodynamics.
4. A fair amount of factual information regarding current industrial and engineering practice in property estimation.

We prepared a set of notes for this course which has been added on and revised each time it was used during the last three years. The notes are dittoed for distribution so we do not require any textbooks. The most often cited reference books are listed below:

A one-semester (14 week) course dealing with biological transport phenomena and biomedical engineering has been developed at Clarkson by the author and taught to seniors and graduate students. Prerequisites for the course consist of previous acquaintance with fluid mechanics, heat transfer, and mass transfer. No background in life sciences is required or assumed.

As the course title suggests, one part of the material covered deals with momentum, heat and mass transport phenomena in living systems, without reference to engineering applications. Another major part of the course, as implied by the second half of the course title, deals with engineering as related to living systems (more specifically, medical engineering concerned with humans). Topics like blood rheology, heat transfer in the body, and mass transfer across cell membranes are typical of those in the biological transport category. Modeling of the body, artificial kidney devices, and artificial heart valves are subjects which fall into the biomedical engineering category.

Besides these two general areas, the course contains a small amount of anatomy and a considerable content of physiology, e.g., circulatory system, kidney, and lung physiology. As can be seen from the course outline, Table I, the course stresses biological transport phenomena in the first half and biomedical engineering in the second half, with physiology interspersed throughout. This sequencing is logical in the sense that a proper consideration of the engineering applications (artificial kidney, etc.) relies on a firm knowledge of the physiological and physical chemical workings of the human body.

One can see from the course outline that a number of topics that could have been included do not appear, for example, nerve impulse transmission, physiological control systems, etc. For lack of time, it was decided to omit those topics, and areas such as bioelectronics (instrumentation), biomechanical devices (artificial limbs), and systems analysis. Many of these subjects seemed to be of questionable value and appropriateness for chemical engineers. It should be mentioned that an advanced follow-up course has also been offered. While this course mainly goes into greater depth on subjects found in the introductory course, some added items (e.g., on nerve impulse transmission) do appear. In general, both courses accent areas where chemical engineers have made their greatest contributions.

There exists no suitable text for the course, and this has been a problem. Most biomedical engineering books in print consist of collections...
David O. Cooney is an associate professor of chemical engineering at Clarkson. He received a BE cum laude from Yale in 1961, and a PhD degree from the University of Wisconsin in 1966. After three years with Chevron Research Company as a research engineer, he joined Clarkson’s faculty in 1969. Dr. Cooney’s research interests are in biomedical engineering, fixed bed sorption, and flow through porous media. He is an avid white-water kayaker and backpacker.

of research or review type articles of a wide variety. It is not uncommon that in any single book only one or two of the topics in the course outline appear. Even then, coverages of those topics are usually unsuitable. Moreover, as mentioned, the course includes a substantial amount of standard physiology, which is usually missing from the more engineering oriented texts (a book just published which appears to be quite suitable for parts of the course is that by Stanley Middleman18). As the basic text for the course it was therefore decided to use Guyton’s *Textbook of Medical Physiology,* a large standard work, as the primary source of material on heart, lung, and kidney physiology, and on several aspects of biological transport, e.g. the elements of blood rheology and membrane transport, and the basics of circulatory system dynamics. For the other topics (or to supplement those in Guyton’s book), handouts consisting of a wide variety of materials are employed. This approach works well enough, but the students would prefer having one large or two small appropriate textbooks.

In preparing lectures the author found the sets of notes by Lightfoot11 and by Keller and Leonard12 to be of great assistance. Parts of Lightfoot’s notes seemed a little too advanced, for the seniors especially, and both references lacked material on certain subjects. However, both works are oriented toward engineers, particularly chemical engineers, and would, if developed further, constitute excellent texts for this type of course.

Each week a 20 minute quiz is given on the previous week’s material. Hour examinations are omitted. Students have the option of taking a conventional three-hour final examination or of submitting a term paper or term project report. This option introduces the opportunity for each student to pursue specific topics of interest in detail without jeopardizing his course grade.

**INTRODUCTORY MATERIAL**

To convey to the student a feeling for the context of present-day advances, and especially the idea that biomedical engineering is not totally new, but an ongoing activity of ancient origin, a brief historical background is given. Mention is made of da Vinci, Vesalius, Sanctorius (inventor of the first fever thermometer), Harvey, Descartes, Hales, Laënnec (inventor of the stethoscope), and later pioneers. From here the course moves to a very general introduction to human anatomy, illustrated by charts. The sizes, locations, and functions of the major organs and other body components are reviewed. Quantitative steady-state “operating data” and time-averaged mass balances for a typical person at rest are quoted. Data include organ sizes, organ weights, volumes of body fluids, respiratory and cardiac frequencies and flow rates, O2 consumption, CO2 production, daily water balances, etc.

Students are assigned the reading of K. B. Bischoff’s paper “A Chemical Engineering View of Bioengineering,” which helps them to see what chemical engineers have done, are doing, and can do in the bio-transport and biomedical engineering areas. Along with this the students are asked to construct a plastic model “Human Anatomy Kit” (Renwall Products, Inc., Mineola, N.Y., $1.69) — a detailed scale model kit containing roughly thirty pieces. After assembling all major organs and fitting them into the proper body cavity locations, the students find that they have learned a great deal about human anatomy.

During the first week, a film, “Man-Made Man,” originally produced for the CBS Twenty-First Century Series, is shown. The film contains footage on artificial organs, organ transplants, and other advances related to the repair or replacement of body parts. This, and seven other films shown during the course (see listing below), greatly stimulates student interest. While most of the films are of college level, a couple are perhaps too elementary. Although these could be deleted...
they are kept in the course for their value in creating variety. They are:

F2 “Control of Body Temperature,” Encyclopedia Britannica Educational Corp. (EBEC), Chicago.
F4 “Control of Body Temperature,” Encyclopedia Britannica Educational Corp. (EBEC), Chicago.
F6 “Work of the Kidneys,” EBEC, Chicago.
F7 “Gift of Life” (describes daily life of an artificial kidney patient), obtainable from National Medical Audiovisual Center, Atlanta.
F8 “Respiration in Man,” EBEC, Chicago.

THE HUMAN THERMAL SYSTEM

This topic is considered next because it allows the student to get back to familiar ground (heat transfer) and enables him to relate his engineering knowledge to a living system. Also, this topic is more “compact” and less complex than, say, mass transport in living systems.

We first quickly review the basic processes of digestion and the conversion of food into metabolic energy. Chemical reaction (stoichiometric) equations and overall energy balances are written. Having learned about heat production, we then consider the quantitative description of heat dissipation from the body’s surfaces via radiation, evaporation, convection, and conduction. A few interesting homework problems in thermal phenomena are listed in Table II. The class reads Eugene Wissler’s paper “A Mathematical Model of the Human Thermal System” to learn how standard analytical modeling techniques can be used in this area. Finally, we consider heat transfer within the body, such as between arteries and veins via tissue conduction and perfusion through connecting capillaries. The development of models for such processes and the setting up of appropriate equations are demonstrated. However, details of their solution are not presented (the advanced follow-up course pursues these aspects). Thermo-regulation mechanisms (e.g., vasoconstriction) are mentioned only briefly.

MODELING THE BODY

The paper by Wissler introduces them to the idea of modeling. This is continued by having the class read Bischoff and Brown’s “Drug Distribution in Mammals.” In lectures we also consider a variety of additional body models which have appeared in the literature. The notions of splitting the body into appropriate compartments, production sources (or sinks for elimination), and fluid streams are taught. Problems of obtaining accurate and meaningful parameter values are discussed. In addition, the general solution schemes for the sets of linear equations which usually result from compartmental analyses are reviewed. The experience in modeling that the student gains here is useful in a large part of the remainder of the course.

FLUID MECHANICAL PHENOMENA

An understanding of blood rheology and of the dynamics of the human circulation is essential to a very wide variety of biomedical problems, including extracorporeal blood flow in artificial organs, studies of capillary-tissue mass transfer, analyses of atherosclerosis, etc. This important area is introduced by a discussion of the composition, properties, and rheological characteristics of plasma and whole blood. The non-Newtonian behavior of blood, effects of rouleaux formation at low shear, the high shear Fahraeus-Lindquist effect, plasma skimming, and other aspects are covered.

The next two weeks are spent discussing the human circulatory system. After describing the
general features — volumes, flow rates, vessel sizes, locations of laminar and turbulent regimes — we consider the structure and properties of vessel walls. The various kinds of wall components, their effects on vessel stability, and their roles in modifying flow pulsations are discussed.

Application of Bernoulli's equation to various parts of the circulatory system are demonstrated in class (these are approximate analyses, neglecting pulsations). Here we show how high pressure is created in aneurisms, why low pressure prevails in stenoses, what the theoretical horsepower of the heart should be, and so forth. Typical homework problems dealing with circulatory system dynamics are cited in Table II.

ARTIFICIAL HEARTS AND VALVES

This subject area, involving many fluid flow problems, is treated next. At this stage of the course the students are anxious to learn about real hardware, and they find this topic quite satisfying from that standpoint. Some discussion of blood hemolysis, protein denaturation, thrombus formation, and the broad subject area of biomaterials comes first. Then various designs for heart valves, total heart replacements, and partial heart substitutes (ventricular boosters and bypasses) are discussed from engineering and physiological viewpoints. A life-sized model of the human heart is displayed and passed around to familiarize the students with the organ under discussion. The section of Eugene Guccione's paper dealing with these devices is handed out for reference. Also, the film "The Human Heart" (another CBS "21st Century" production) is shown. This excellent film contains demonstrations of artificial heart construction, surgical implantation of heart assist devices and interviews with noted surgeons (Barnard, DeBakey).

BIOLOGICAL MASS TRANSPORT

The second half of the course concentrates on topics involving mass transport phenomena to a large degree, especially membrane transport. We begin by reviewing the basics of ordinary, or passive, transport—diffusion resulting from concentration, electrical potential, or pressure gradients (no carriers, no biological energy consumption). This material is familiar to the student from earlier coursework.

Next we consider the structure, composition, and permeation properties of biological membranes. The importance of lipid solubility, presence or absence of "pores," and effects of solute character are pointed out. Facilitated and active transport mechanisms are discussed in some detail. With respect to the former, equations are written for the system O₂-hemoglobin-oxyhemoglobin to illustrate the effects. With respect to the latter, little of a quantitative nature can be written. However, details of proposed "Na-K pump" mechanisms are scrutinized.

Having obtained a background in passive, facilitated, and active transport the student is then ready for consideration of the natural lungs and kidneys and their artificial counterparts.

KIDNEYS—REAL AND ARTIFICIAL

Two lectures are spent on the physiology of the natural kidneys. Impressive data are given which convince the student of the tremendous capacity, selectivity, and efficiency of the human kidneys. Countercurrent concentration of urine via active transport is discussed in detail. This material gives the student the proper perspective toward the next subject — artificial kidneys.

Leonard and Dedrick's paper, "The Artificial Kidney — Problems and Approaches for The Chemical Engineer" provides a good reference here. The major kinds of artificial kidneys in current use (coil, flat plate, hollow fiber) are reviewed, and their operating characteristics discussed. Advantages and disadvantages of each type are made clear. Mathematical descriptions of these devices are formulated on a simplified basis. Consideration is also given to modeling the artificial kidney-patient system as a whole (using a compartment model for the patient). Rough calculations of treatment times for typical patients and dialyzers are also performed. An excellent film (F7) showing actual clinical and home dialyses complements the lectures nicely. Demonstration units of coil and hollow fiber artificial kidneys, set up and run with "blood" (colored water), are used here also. Finally, some mention is made of "novel" and alternative approaches to uremia e.g., fixed-bed sorption devices, ultrafilters, peritoneal dialysis.

LUNGS—REAL AND ARTIFICIAL

The course format here is virtually identical to that relating to real and artificial kidneys. Two lectures on the physiology of the natural lungs are given, with emphasis on the kinetics of O₂-CO₂.

(Continued on page 185)
A Course in
MODELING

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For a number of years our Department taught a rather traditional course along the lines of Mie­kley, Sherwood and Reed’s Advanced Mathematics in Chemical Engineering. The content varied a bit with the inclinations of the instructors but was, mathematically, “soup to nuts.” Such a course is literally applied mathematics: take a large measure of calculus from ordinary to partial and another measure of examples and problems from Chemical Engineering. Blend well and serve.

Over the years it was found that the students had little difficulty with the mathematical content. Once the bag of mathematical tricks had been presented and practiced, few had difficulty in finding the right tool for the given mathematical situation but this was not the case with the physical situation. If the student could formulate the problem, he could solve the solvable mathematics; inevitably, the problem was in the formulation. There seems to be a lesson in the organization of all engineering math texts: a dozen chapters on mathematical tools and one on formulation or modeling. Perhaps we should try teaching modeling, and pass along the mathematical stuff as we go, almost as entertainment!

The first thing that had to go was a one-term marathon. After the mathematics is crammed in, there is no time for contemplation of what one is actually doing when obtaining a model, or one of several possible models, for a situation, nor for carrying out with any deliberateness an analysis of what one has done in the process of going from a problem statement to the mathematical statement. The second thing that had to go was the title! Start with “Advanced mathematics...” and the students’ minds are already made up that they are there to learn mathematics, the preliminaries being just trying to cast this week’s problem into this week’s mathematics. So we called it, naturally, Mathematical Modeling in Chemical Engineering, with a I and a II.

Splitting the conventional content of an advanced calculus course into two terms is not a hard thing to do. We proceeded by straddling the undergraduate transition, the first course being offered at the Senior level (ChE 407), and encompassing mostly problems in one dimension, and the second offered at the graduate level (ChE 507), but available to qualified undergraduates, and extending into multidimensional problems. But if a structure of mathematical dimensionality can be called a vertical ordering of mathematical content, the philosophy and practice of modeling is orthogonal — horizontal — and cannot be divided in the same fashion. In fact, the same concepts of modeling apply unaltered to both categories of mathematics. The pedagogical problem, then, is to provide for the students taking both courses an interesting second course using the same philosophy of modeling superim-

### TABLE 1. Interaction of Mathematics and Modeling

<table>
<thead>
<tr>
<th>MATHEMATICS</th>
<th>MODELING</th>
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<tbody>
<tr>
<td>ChE 407</td>
<td>1. Problem Definition</td>
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<td>2. System(s)</td>
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<td>Coordinate systems</td>
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<td>Assumptions and Presumptions</td>
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<td>Notation, symbols</td>
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<td>Differential balances</td>
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<td>Laws, correlations</td>
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<td>3. Preliminary Combination</td>
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<td>Initial Conditions</td>
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<td>Boundary conditions</td>
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<td>Constraints</td>
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<td>5. Simplification</td>
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<td>Dimensional considerations</td>
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<td>6. Selection of Solution Procedure</td>
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<td>Mathematics</td>
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<td>Interpretation</td>
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<td>7. Calculation</td>
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<td>8. Reporting</td>
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<td>ChE 507</td>
<td>9. Calculation</td>
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<td></td>
<td>10. Reporting</td>
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</table>

What differs from tradition is the strong emphasis on modeling blended with mathematics. The required text is “Your Last Calculus Book”...
Robert H. Kadlec has a BS from the University of Wisconsin, and MS and PhD ('62) from the University of Michigan, all in chemical engineering. He has taught at Michigan since 1961. His current research interests include modeling and simulation, in the areas of unsteady processes, automobile emission control reactors, and ecological systems. (left photo)

Rane L. Curl received both his BS and ScD from MIT, finishing in 1955. After six years with Shell Development Company in Emeryville, California, he spent one year at University College London and two at the Technische Hogeschool Eindhoven, before coming to Michigan in 1964.

His teaching interests include rate processes, mathematics and statistics. His research is in areas of liquid-liquid dispersion interaction, mass transfer with and without chemical reaction and karst geomorphology.

posed upon the higher dimensional mathematics. The key to doing this is to introduce more advanced formulation methods along with the more advanced “equations.”

This interaction is shown in Table 1. The list of mathematical topics is typical, but not inclusive of all topics that have been treated. There is little new here. The complementary list of modeling topics is also unoriginal; they are necessary no matter how “advanced mathematics” is to be taught. What differs from tradition is the strong emphasis on modeling blended with mathematics. The required text is “your last calculus book”; we can use no other as we seek to avoid giving modeling a mathematical framework.

WHY MODEL

There is a single statement which sums up the reasons for modeling: It allows the logical restructuring of descriptions, providing insight and the capability to produce quantitative results in response to questions. It is no accident that the fields of study in chemical engineering have organized themselves according to the type of question to be answered and the corresponding modeling and restructuring procedures. These areas, together with the general question asked are as follows:

- **Research.** What are the basic laws, which when used in the structure representing the system, will produce the observed effects?
- **Parameter and Property Evaluation.** What are the numerical values of the symbols which characterize the system (parameter) or the material (property) being described?
- **Design.** Among the parameter and property values which we may choose, what set of values will produce the desired result?
- **Optimization.** Among the sets of values which may be chosen for a given process, what set will yield the best value of the desired result?
- **Simulation.** Given all the parameters and values and functions necessary to determine the operation of the process, what result may one expect?
- **Control.** Given a process and a specified mode of operation, how can one ensure that it will continue to operate in this fashion?

Only the first three of these were generally thought to be important in the quantitative modeling sense until approximate a decade ago. The remainder of the questions were asked, but answering them remained an art until machine computation appeared on the scene.

One particularly important aspect of communication is the ability to read the current literature in an area of interest. The vast majority of contemporary technical writing depends heavily upon and is oriented toward a mathematical approach. To be conversant in these terms requires abilities in both model building and in mathematics.

There is in this connection a common statement that needs a mild rebuttal. It is: “I am (or plan to be) a manager, so I do not care about this mathematical stuff. I need to learn how to deal with people.” This is incorrect by virtue of being overstated. It is necessary to use manpower to the limit of its ability in a competitive environment, and to do so requires an understanding of these abilities. Therefore it is imperative to understand mathematical modeling from the viewpoint of “know what it can do”, so that one can properly direct the efforts of those who “know how to do.”

THROUGH THE LOOKING GLASS

The solution of a modeling problem is a tortuous path, traversed with a cloudy mirror before the engineer. Only experience can give clues as to where the path is leading—while all
the work behind is visible, including errors. A prescription on how to proceed is very necessary.

Logically, the first question is: Where am I going? A clear problem statement must be had. To illustrate:

1. **Problem Statement:** Glycerin is to be heated with condensing Dowtherm A at atmospheric pressure. The glycerin enters a 360 ft. multipass exchanger at 180°F. The tubes are 1/4 inch BWG 12 copper. The glycerin mass flow is \(2.7 \times 10^6 \text{ lb m}l/\text{ft}^2\text{hr per tube}\. Calculate the exit glycerin temperature.

Next, all pertinent information is assembled. It helps to draw a picture of the physical process to be described. Labeling such a sketch provides instant organization of some nomenclature; the whole can be listed eventually. Now select the portion of the system which can be described by the basic laws available. This may be an entire process, a process unit such as a reactor, or a differential portion of a process unit if spatial variations are anticipated.

2. **Assembly of Information.**

   **Diagram:**

   ![Diagram of glycerin heating process](image)

   **System:** \(V = \text{glycerin within the exchanger}\)
   
   **Nomenclature:**
   - \(V\) = length, ft
   - \(L\) = total tube length, ft
   - \(T\) = temperature
   - \(G\) = mass velocity, \(\text{lb}_m/\text{ft}^2\text{hr}\)
   
   **Subscripts:**
   - \(i\) = inside tube
   - \(o\) = outside tube
   - \(e\) = entrance to exchanger tube
   - \(L\) = exit from exchanger tube
   
   **Subsystem:** \(\Delta V = \text{glycerin within a differential length of tube}\)

The selection of the basic laws — both kind and number—is deeply affected by the assumptions and presumptions made concerning process behavior. There is an often-neglected difference between these which should be pointed out. An assumption refers to something taken for granted, and hence is usually not checked. A presumption is a belief unsupported by evidence—or in other words an assumption about which we feel uneasy. There is no safe course in making assumptions and presumptions. Assume too much and you get a wrong answer; assume too little and complications prevent getting any answer. Presume too much and you are called ignorant; presume too little and you are called a coward. The proper approach is to occupy the most defensible position while obtaining results in the desired length of time.

   **Presumptions:**
   1. Constant properties
   2. Turbulent flow on tube side

   **Assumptions:**
   1. No Multiple-tube effects (horizontal arrangement, one tube thick)
   2. Constant (saturation) temperature for Dowtherm
   3. Arithmetic average inlet film temperature difference, can be used in the correlation for condensing coefficient
   4. Steady state

The selection of the basic laws to be used is influenced somewhat by the choice exercised above, and in turn influences that choice. Should a statistical or deterministic approach be taken? Are we worried about time behavior? Is it necessary to know distribution of variables within a process unit? We must discard some of the very small, the very large, the very fast, the very slow aspects of the process, depending upon the desired result. A partial explanation is all we can ever expect.

There are certain **axiomatic rules** which are not violated except under extremely unusual circumstances, and may be considered to be universally applicable. In contrast, there are also **descriptive laws**, which apply only in a limited number of circumstances and which are never universally applicable. This latter group originates either from a theory regarding material behavior in a given situation, or from the correlation of a body of physical data.

The remaining laws, which apply to only specific situations, may be divided into two groups. They are either algebraic statements of the observed relations between system variables or statements of the dependence of the rate of an elementary process variables.

There remains a class of mathematically true statements which are in no way related to the real world. Certain definitions bear a remark-

**Perhaps we should try to teach modeling, and pass along the mathematical stuff as we go, almost as entertainment!**
able resemblance to either basic laws, rate laws or correlative equations.

Axiomatic Laws: Conservation of Energy
\[ (c_1 c_1 (\rho / \alpha)^1/4) T_1 \delta x - (c_1 c_1 (\rho / \alpha)^1/4) T_1 \delta x + q(\alpha / \delta x) \]

Rate Laws: Heat Flow
\[ q = \frac{U}{T_0 - T_1} \]

Correlations:
\[ \text{Nu} = 0.023 \ Re^{0.4} \ Pr^{0.4} \]
\[ h = 0.725 \left( \frac{k A}{D^4} \right)^{1/4} \]

Added Nomenclature:
\[ G = \text{mass velocity, lb/ft/hr} \]
\[ D = \text{diameter, ft} \]
\[ C = \text{heat capacity, BTU/lb °F} \]
\[ \rho = \text{density, lb/ft}^3 \]
\[ \mu = \text{viscosity, lb/ft/hr} \]
\[ \kappa = \text{thermal conductivity, BTU/ft °F} \]
\[ Re = \text{Reynolds number} \]
\[ Pr = \text{Prandtl number} \]
\[ h = \text{heat transfer coefficient, BTU/ft °F} \]
\[ U = \text{overall heat transfer coefficient, BTU/hr ft °F} \]
\[ R = \text{heat transfer resistance, hr ft °F/BTU} \]
\[ Q = \text{heat transfer rate, BTU/hr ft} \]
\[ g = \text{acceleration of gravity, ft/hr}^2 \]
\[ \lambda = \text{latent heat of condensation, BTU/lb} \]

Subscripts:
\[ f = \text{film (outside)} \]
\[ w = \text{wall} \]
\[ F = \text{Fouling} \]

Following this listing of the mathematical relations, a certain amount of "condensation" is usually possible. Added bits of information, such as boundary conditions, are found to be necessary.

3. Combination. Divide energy balance by
\[ \left[ (c_1 c_1 (\rho / \alpha)^1/4) \right] \]
and let \( \Delta x \to 0 \).

\[ \frac{dT}{dx} = \frac{Q}{G c_p D} \]

Substitute rate law:
\[ \frac{dT}{dx} = \frac{4U}{G c_p D} (T_0 - T_1) \]

4. Boundary Conditions.
\[ \text{at} \ x = 0, \ T_e = 180° F = T_{i0} \]

5. Simplification.
\[ A = \frac{4U}{G c_p D} \]
\[ \text{Then:} \]
\[ \frac{dT}{dx} = A (T_0 - T_1); \ T_1 (a) = T_{i0}; \ A = A (T_e, T_{i0}) \]

Having formulated a mathematical structure, it is quite unlikely that one may immediately proceed to compute the desired answer. It is far more likely that the next step is to restructure the math problem—e.g., solve differential equations.

Modeling allows the logical restructuring of descriptions, providing insight and the capability to produce quantitative results in response to questions.

\[ \int_{T_{i0}}^{T_{iL}} \frac{dT}{T - T_{i0}} = \int_{a}^{A} \frac{d\xi}{\xi} \]
\[ T_{iL} = T_0 - (T_0 - T_{i0}) e^{-AL} \]

7. Numerical Results. The information given plus data on the two fluids, yield a value of \( A = 4.18 \times 10^{-9} \) and \( T_0 = 495.8° F, T_{iL} = 425.3° F \)

8. Discussion of Results. With the assumptions given, the glycerin is heated to 425.3° F. However, a check of the constant property assumption shows that it is seriously in error. For example, at 180° F, \( \mu_c = 29cp; \) at 425.3 F, \( \mu_c = 1.2cp. \) Therefore, it appears necessary to "iterate" back to step 2 and change the presumptions. Only part of the next iteration will be shown here. Presumption 1 must be abandoned; flow on the tube side is confirmed to be turbulent.

Words and numbers are ultimately required from the model. One does not submit a differential equation to management, nor does one frame a computer program and hang it on the distillation tower. It is the responsibility of the modeler to communicate his results either by interpretation, or by providing statements so clear that others can interpret them easily and without possibility of error. This feature of modeling is frequently ignored, fostering battles of misunderstanding between the model builder and the potential model user.

Figure 1. A Model Building Algorithm with Iteration
In the example that we have been carrying along as a guide, we find that we aren’t ready to communicate our results as they violated a presumption. An iteration of the model is required. However iterations are possible at several different levels, as shown in Figure 1, which rests on the lists of modeling steps in Table 1.

2-II. Assembly of Information.
Assumptions:
1. Temperature dependent fluid properties.
2. Turbulent flow on tube side.
3. No multiple tube effects.
4. Constant Ducterm temperature.
5. Variable film temperature, and Temperature difference.

New correlations are needed, and the solution method becomes a computer technique.

8-II. The value of the exit temperature is 464.7°F.

PEDAGOGY

It is moderately difficult for the instructor, and unsatisfactory for the student, to spend much time talking about the philosophy or even the structure of modeling. It seems so self evident that it is boring—but still the students go astray simply by virtue of overlooking a modeling step. Therefore, to make all this work, and to make it interesting at the same time, a variety of pedagogical tricks have been developed and used. These have included:

1. Omit problem statement. The “problem” is presented as a demonstration: a vessel is allowed to drain through a square hole and the level measured vs time; a hot sphere is immersed in a vessel of water and its temperature measured; a beaker of molten paraffin is allowed to solidify. Model this situation is the instruction. This focuses thought upon securing a precise problem definition. The students must pry it out of both the instructor and reality.

2. Give problem solution. A problem from a preceding course (where it is presumed that the principles of modeling had not been taught!) is chosen and the instruction is to recast it into the algorithmic solution format given in Figure 1. This focuses the student’s attention upon procedure: the work of “solution” has been completed in advance within some other procedure, be it derivation or formula-plugging.

3. Trial by fire. A student is asked to solve a problem before the class, with no prior preparation. The whole reasoning process is thus brutally exposed. A kinder approach is to successively question class members to develop the model step-by-step, following the modeling algorithm of Figure 1.

4. Tweak by paradox. A “completely logical” example is presented, which leads to a clearly ridiculous result. The location of the flaw in reasoning is a superb educational device.

5. Math made illegal. A fairly detailed report, containing no math but explaining the model and results, is requested on a problem.

BELL (Continued from page 157)

The lecturer has a small monitoring screen on the desk in front of him that shows exactly what is going on to the viewers. (The monitor is an insidious and ruthless device: lecturers have been known to start yawning in boredom while watching it.) The studio audience mostly watches the two TV screens, because that’s where the action is when the lecturer is working on the note pad; this is somewhat distracting to an experienced lecturer, who relies upon eye contact to see if the audience is with him. I don’t use the board because it is hard to remember to work in properly scaled modules so that the whole image fits the TV screen and yet is legible. This is readily controlled by using a 6 in. by 8 in. buff-colored note pad. The material to be presented in class is written or drawn upon the pad in yellow ink, which is readily visible to the lecturer and nearly invisible to the camera; during the lecture, the notes, etc. are made visible to the audience by writing over them with a black felt-tip pen. (By forcing the lecturer to do the writing, the speed of the presentation is held closer to the speed at which the students can make notes.)

Acclimatization to the TV system took only two or three lectures. The most important single change that I noticed was that I was better prepared to lecture when I came to the studio. Having to prepare the notes in yellow ahead of time not only forced me to review, but also to organize the material so that the contents of each sheet made sense.
A Course in
APPLIED SURFACE CHEMISTRY

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Few undergraduate or graduate curricula contain a course in applications of surface phenomena, yet the need for background in applied surface chemistry arises daily in the industrial production of foams, detergents, emulsions, paper, and textile fibers, as well as in processes involving adsorption, such as reinforced plastic and rubber systems, heterogeneous catalysts, and crystallization. The properties of the material surface are also important in lubrication problems of certain types and in the selection of materials to be used for biological applications, and in numerous other situations. Since such systems are encountered so frequently in almost any manufacturing process or, in fact, in most experimental research projects, there appears to be a need for the teaching of a few fundamental concepts combined with practical applications.

My own interest in this area began with graduate courses in colloid chemistry and polymer chemistry. But it was not until I was involved in industrial research that I realized the need for a more practically-oriented type of approach. I was working for what was then called the Silicones Division of Union Carbide Corporation, and, of course, most silicone products are sold because of some beneficial surface property. Also at that time I noticed that the same fundamental ideas were applicable to many different kinds of products such as fibers, rubber, foams, and waxes. I'm sure that this is obvious to someone knowledgeable in the area of surface chemistry, but it was quite a revelation to me at the time.

When I came to the University of Virginia there was a course called, appropriately enough, Applied Surface Chemistry. So after I expressed an interest in developing a course which would apply certain fundamentals in many broad areas, this seemed the perfect place to do it, although the course had previously emphasized somewhat different aspects. I felt that the only prerequisite necessary for the student should be a course in physical chemistry, and that the course should be offered as an elective for seniors and graduate students. I see no need for differentiating between undergraduate and graduate students in such a course as both really have the same background in surface chemistry (i.e., relatively little).

The reception of the course at the University of Virginia has been both encouraging and somewhat enthusiastic. A number of students take the course each year, both seniors and graduate students, and from other departments as well as from Chemical Engineering. The students usually quickly find an application for the material. A number of graduates have written me that they were finding numerous uses for the course material in their subsequent jobs, whether in production, development, or research. The course is also a natural one for a short-course because it can be shortened without deleting any of the important concepts simply by not covering as many applications. I have taught it both as a one-week course and as a two-day course in the Today Series of the AIChE.

With this background, then, let me now describe the content. But first, let me stress again my belief in having a little knowledge go a long way; that is, using many applications which really involve the same fundamental ideas. This philosophy will be quite evident in the outline of the course, and is also a criticism one might make. Some people may feel that it is better to go into some areas deeply, and, of course, that is a good approach in many instances. However, I feel that the survey approach is better for this course, which is, after all, only the first one in a possible series of surface phenomena courses.

John Gainer earned the BSChE from West Virginia University, the MS from MIT, and the PhD ('64) from Delaware. His industrial experience includes several years in the Silicones Division of Union Carbide. John was Visiting Fellow, Karolinska Institute, Stockholm in 1971. His research interests include mass transfer, polymer and surface chemistry, diffusion in biological systems, and enzyme engineering.

that book as the text for the course, although I really do not use it to any great extent. Some of the students feel that perhaps I should not assign it as an official textbook, but instead make it an optional reference. My reasons for not doing so are based on two observations: (1) students rarely refer to suggested reference books, and (2) I think that it is quite valuable to have a good compilation of experimental methods for measuring surface phenomena, which Adamson certainly is. Thus by becoming at least somewhat familiar with the material in the book, the students will know in the future how to go about setting up a given type of apparatus. In order to accomplish this familiarity, I usually suggest short reading assignments every day in Adamson. There are other books which one could use for such a course, but the variety of experimental apparatus covered in Adamson is much greater than in other texts, thus making it a valuable reference book for future use.

An Outline of Applied Surface Chemistry

I. Introduction concerning the importance of knowing surface characteristics.

II. Thermodynamics of Surfaces
   A. Concept of surface free energy
   B. Derivation of surface thermodynamic properties from surface tension.

III. Capillarity
   A. Physical definition of surface tension
   B. Fundamental equation of capillarity, and influence of surface geometry on surface tension.
   C. Ways to measure surface tension, and ways to estimate it from other data.

D. Influence of surface tension and size on thermodynamic properties of small drops.

IV. Concentration Effects on surface tension
   A. Gibb's adsorption and surface excess concentration
   B. Surface active agents
      1. Levelling agents
      2. Detergents
   C. Micelle formation

V. Films and Monolayers
   A. Formation of monolayers on liquid surfaces
      1. Surface pressure
      2. Surface viscosity
      3. Use as evaporation suppressants
   B. Formation of a liquid film on a liquid surface
      1. Work of adhesion and of cohesion
      2. Spreading coefficients
      3. Antifoaming agents

VI. Liquid–Solid Interfaces
   A. Development of Young–Dupré equation
   B. Definition of work of cohesion, work of adhesion, and spreading coefficient
   C. Wetting agents
   D. Coatings for water repellency
   E. Further discussion of detergency
   F. Ore flotation

VII. Liquid–Liquid Interfaces
   A. Emulsions
      1. Factors affecting stability
      2. Emulsifying agents
   B. Microencapsulation
   C. Emulsion polymerization

VIII. Foams
   A. Gibb's theory of elasticity
   B. Marangoni effect

IX. Solid–Solid Interfaces
   A. Lubrication, stressing boundary lubrication in particular
   B. Coatings for water repellency
   C. Electrical properties of surfaces.

X. Fluid–Solid Interfaces
   A. Adsorption
      2. Physical adsorption versus chemisorption
      3. Heterogeneous catalysts
         a. Models for unimolecular and bimolecular reactions
         b. Temperature dependency
   B. Adsorption from solution
      1. Ordinary monomeric solutes
      2. Polymers
         a. Reinforced plastics and rubber

XI. Miscellaneous
   A. Nucleation and crystal growth
   B. Membranes
   C. Electrical properties of surfaces.

As is readily apparent from the preceding outline, the scope of the course is quite large. Thus, of necessity, the topics are not covered in great depth. For example, one could easily develop a course merely on electrical properties of surfaces, but, for a first course, I believe that the survey is better. Basically, I try to empha-
size that surface tension is important in various systems, and that it is a function of geometric shape, temperature, concentration, and electrical charge. Most of the topics build on this.

One of the most important aspects of any course, in my opinion, is to have daily problem assignments. There is no easy source of problems for all of these areas. However, I have compiled a large set of what I call "pseudo-industrial applications" which I assign each time. These problems have come from my experiences and reading, and are, for the most part, designed to put the student in a position of a "trouble-shooter" or development engineer. I am listing two examples of such problems at the end of this article. In addition, I ask each student to write a critical review of one article in the literature (of his choice) toward the end of the course. I think that this is quite valuable in demonstrating to the student that he can now understand much of the literature concerning surface phenomena, at least in a superficial sense.

One of the topics I would like to cover in more detail is that of biomaterials. Last year, while I was on leave, another member of our staff taught this course and added a section concerning this, especially in relationship to thrombus formation on implants. This has now been expanded and next year a course will be offered at the University of Virginia covering just biomaterials. Thus the need for me to add material on this subject no longer exists, and the students will be able to learn this area from teachers much more expert than I. However, I believe that it should be kept in mind when developing any general surface phenomena course.

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**ChE problems for teachers**

Problems from Professor Gainer's course on "Applied Surface Chemistry."

1. A. As Product Manager of Emulsions, Inc., you are responsible for the new product composition. Your laboratory has given you the following data which was obtained at 25°C:

<table>
<thead>
<tr>
<th>Compound</th>
<th>Density (g/ml)</th>
<th>Mol. Wt.</th>
<th>Viscosity (cp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>For dispersed phase:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>0.8</td>
<td>100</td>
<td>0.8</td>
</tr>
<tr>
<td>B</td>
<td>1.0</td>
<td>150</td>
<td>0.9</td>
</tr>
<tr>
<td>For continuous phase:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>0.8</td>
<td>200</td>
<td>3.0</td>
</tr>
<tr>
<td>D</td>
<td>0.8</td>
<td>210</td>
<td>5.0</td>
</tr>
</tbody>
</table>

A and B are both relatively insoluble in both C and D.

a. Which system of the four possible systems will make the most stable emulsion at 25°C without the use of an emulsifier?
b. Will this be the most stable emulsion at 50°C? Do you need more data? If so, what?
c. Name two ways to break the emulsion.

B. It has now been decided to use an emulsifier to stabilize the emulsion picked in problem 1A. You have three (3) emulsifiers to choose from:

<table>
<thead>
<tr>
<th>Emulsifier</th>
<th>Mol. Wt. (g/l)</th>
<th>Solubility (g/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>E1</td>
<td>150</td>
<td>0.08</td>
</tr>
<tr>
<td>E2</td>
<td>150</td>
<td>0.15</td>
</tr>
<tr>
<td>E3</td>
<td>250</td>
<td>0.08</td>
</tr>
</tbody>
</table>

a. List the emulsifiers in order of stabilization (list the emulsifier producing the most stable emulsion first, etc.) Why did you choose this order?
b. Are there other factors to be considered in picking the best emulsifier to be used commercially? If so, what data do you need?

2. You have been hired by the Super Detergent Company. It is a small company, and you are their expert in surface chemistry. The boss has an idea for a new detergent which must be commercially competitive. He calls you in his office, hands you a box of the new detergent (Super X) and tells you that he has the following information about the detergent:

- The organic part of the detergent molecule contains approximately 10 carbon atoms. (Molecular weight is 260).
- A surface tension–concentration curve has been obtained as is shown in Figure 1.
- Other commercial detergents of this type sell for 16 cents per pound with recommended use of 1.2 ounces per gallon at 10°C.
- Super X will sell for 18 cents per pound.

It will be your job to evaluate Super X as follows:

a. What minimum concentration of Super X must be used (in ounces per gallon) for maximum detergency? Is Super X competitive with other detergents? Show comparative costs.
b. Would you recommend this amount to be used for washing at higher temperatures? Explain.
c. Can you make any recommendations about making a new detergent, Super XX, which might be cheaper to use than Super X provided that the manufacturing costs of Super XX are the same as for Super X?

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FIGURE 1

Concentration, moles/liter of solution

FALL 1972
Thoughts About Our First Graduate Courses In
MOMENTUM, ENERGY, AND MASS TRANSFER

JOHN C. SLATTERY
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Evanston, Illinois 60201

Sometimes I feel that our department has had almost continuous discussions over the last fifteen years about the objectives to be sought in teaching graduate courses. A positive effect of these discussions has been to encourage experimentation.

Among other courses, a two-quarter sequence in momentum, energy, and mass transfer has evolved over the past seven years. To help you understand the approach that I have taken in presenting this area to our students, let me first discuss my objectives.

I have difficulty in talking about our graduate courses without first saying something about our concept of the undergraduate sequence. So let me begin there.

OBJECTIVES OF UNDERGRADUATE SEQUENCE

With any undergraduate engineering course, we have two objectives. We would like to help the student both understand the ideas underlying the subject and achieve some facility with the most useful approaches to analyzing practical problems.

When teaching our undergraduate sequence in momentum, energy, and mass transfer, I begin with fundamentals. These are the mass, momentum, and moment-of-momentum balances, if we are discussing fluid mechanics. But I do not spend much time in solving the corresponding differential equation of continuity or the differential equation of motion. A greater variety of experimentally motivated problems is open to analysis by undergraduate students in a relatively short period of time, if the emphasis is placed upon the integral (macroscopic, system, or control-volume) balances.

There is at least one difficulty with placing this much emphasis on the integral balances in the undergraduate courses. Assumptions are required that must be justified by experience, by one's intuitive feel for a physical situation, or by available experimental data. The students need assistance here. I help them gain some experience by discussing the qualitative aspects of real flows and by having them perform as many experiments as possible within our time limitations.

OBJECTIVES OF GRADUATE SEQUENCE

Our objectives are much the same in the beginning graduate sequence, but the emphasis is different. I stress the fundamentals feeling that, the more precisely a person understands the approximations which he is making in analyzing a given situation, the more likely it is that he will be able to make a correct judgment about their applicability.

This beginning sequence is recommended both for those who are seeking a terminal M.S. degree as well as for those who are considering a Ph.D. Our department encourages students to develop a broad and versatile background during their year of M.S. study. In designing this sequence, I have tried to keep in mind that it should form a firm foundation upon which the graduate can build his "engineering experience" after he leaves school.

This does not imply that a terminal M.S. candidate should have the same course background as a Ph.D. man. To supplement his initial sequence, we regularly offer courses that cover limited aspects of the area in greater depth: Applied Transport Processes (applications of fundamentals in the design of commercial equipment and processes), Electrochemical Engineering, Heat Transfer, Physiological Transport Processes, Rheology.

ROLE OF MATHEMATICS

An instructor must quickly decide what role vector and tensor analysis will play in his lectures. Courses in applied mathematics are important. But no matter whether they are taught in mathematics departments or engineering departments,
John Slattery received his degrees in ChE from Washington University (BS) and the University of Wisconsin (MS and PhD). In 1959 he joined Northwestern University, where his current research interests are interfacial behavior and multiphase flows.

physical problems are introduced merely to illustrate the mathematics.

In teaching a course in momentum, energy, and mass transfer, physical problems are our primary concern. Mathematics is used to illuminate the physical ideas. It is a tool or language rather than the objective.

Tensor analysis is the language in terms of which mass, momentum, and energy transfer can be presented in the simplest and most physically meaningful fashion. This does not mean that every student should be capable of transforming the equation of motion from one curvilinear coordinate system to another. That capability will be important for Ph.D. students who are going to specialize in this area. Everyone else will find that their needs are almost always filled by tabulations of the various differential equations in cylindrical and spherical coordinates.

Rather, it is most important for a student to learn to think about physical problems in terms of vectors and tensors. I would like a student to think of a velocity vector as a directed line segment or arrow. A second-order tensor is a transformation of one vector into another. He should visualize the stress tensor as transforming the unit normal to a surface into the stress vector acting upon the surface.

Because tensor analysis is the language, I begin my lectures by introducing it. But I do not recommend that all the details of tensor analysis be explained at the beginning. I have found that it is easier to retain the class interest, if no more than one or two days are spent in reviewing vector analysis before we begin kinematics. Thereafter, explaining the mathematical notation becomes an inseparable part of my discussions of the transfer processes. For example, I make no attempt to introduce the concept of a second-order tensor before it becomes necessary in the derivation of the equation of motion.

I want the student to realize that mathematics can be used to clarify engineering problems rather than to obscure them.

**APPROXIMATIONS**

The objection is sometimes raised that it is really useless to spend much time in developing analytic solutions to problems in momentum, energy, and mass transfer, since the situations that can be handled in this manner are trivial. This is obviously an exaggeration, but there is a point to be made: Most interesting problems either require numerical solutions or are susceptible only to approximate solution.

My feeling is that the best way to introduce this material is through the use of problems that can be solved analytically. These problems are required preparation for those who wish to study more sophisticated problems numerically. It seems unreasonable to attack an involved problem if the straightforward ones are still giving you trouble. As a further practical matter, analytic solutions for limiting cases are highly desirable in order to check the validity of whatever numerical work is performed.

It is also true that most interesting problems are susceptible only to approximate solutions. There are at least four classes of approximations that should be recognized by a student.

1. **Idealization of the physical problem.** Sometimes the physical problem in which we are primarily interested is too difficult for us to handle. One answer is to replace it by one that has most of the important features of the original situation, but that is sufficiently simple for us to analyze. A good example is provided by flow through a tube. An experimentalist is always concerned with flow through finite tubes, but sometimes the entrance and exit regions are of lesser importance to him. In this case, we can replace the real problem by an idealized one in which entrance and exit effects are negligible: flow through a tube of infinite length.

2. **Simplifying the differential equation.** Even after such an idealization, the resulting mathematical problem may be too difficult to solve. We
With any undergraduate course, we have two objectives . . . to help the student understand the ideas underlying the subject and achieve some facility with useful approaches to analyzing practical problems.

may wish to consider a limited case in which one or more terms in a differential equation are neglected. I place special emphasis upon the way in which one should argue to arrive at such an approximation. The classic examples of such arguments are provided in the context of fluid mechanics: creeping flow (for small Reynolds numbers), potential flow (for large Reynolds numbers outside the immediate neighborhood of phase interface), and boundary-layer theory (for large Reynolds numbers in the immediate neighborhood of a phase interface).

3. Integral averages. Many times our requirements do not demand detailed solutions of the differential balances. Perhaps we are interested only in some type of integral average. There are four types of averages that have been found useful in the literature. The traditional approach to turbulence is integral in terms of time-averaged variables.

I want the student to realize that mathematics can be used to clarify engineering problems rather than obscure them.

Area averages are useful in justifying one-dimensional descriptions of flows. I use the concept of local volume averages in discussing momentum, energy, and mass transfer in porous media. Finally, there are the integral balances that are nothing more than averages over arbitrarily defined systems.

4. Mathematical approximations. This is really the problem with which one is primarily concerned in carrying out numerical solutions. A mathematical approximation is applied repeatedly in order to arrive at a solution for a differential equation or the value of an integral.

BOOK

I have recently published a book ("Momentum, Energy, and Mass Transfer in Continua," McGraw-Hill, 1972) that is based upon the lectures I have given in our beginning graduate sequence over the past seven years. It should give you a better indication than any course outline as to how I have implemented these ideas.

The appendix on tensor analysis has been written with three types of people in mind. Only some of the sections are marked as required reading for the many first-year students who are anxious to consider applications as quickly as possible. Other sections are suggested for those students who are more curious about the foundations of continuum mechanics. The complete appendix is recommended for those who wish to do serious research in any of the subareas of momentum, energy, and mass transfer.

Following an introductory chapter on kinematics, Table 1 indicates how I have devoted three chapters to momentum transfer, three to energy transfer and three to mass transfer. For each transfer process, there is one chapter (Chs. 2, 5, and 8) concerned with the fundamental postulates and descriptions of material behavior. A second chapter (Chs. 3, 6, and 9) is devoted to solutions of the differential balances. Considerable emphasis is placed upon the limiting cases that correspond to large or small values of particular dimensionless groups. Finally, there is a third chapter (Chs. 4, 7, and 10) concerned with the integral averaging techniques. It is here that I consider turbulence, flow in porous media, and the various integral balances. I make a particular effort in these sections to discuss the preparation of the empirical data correlations that often must be introduced when integral averages are used.

While I hope this book will be useful to others, I recognize that many instructors feel a textbook is inappropriate for a graduate course. In a sense, I agree with them. An instructor should never feel obligated to follow a book with a graduate course. He should experiment with the new approaches and the new ideas developing in the literature. Chemical engineering has never been a static field and there is every reason to believe that even greater changes are in store for us.

THE CHOICE

Students and faculty interested in either tak-

(Continued on page 197)
In most respects, this young woman is like us all. Except that she lost her kidneys.

And if we never think twice about purifying our blood, she thinks about nothing else. Because while we rely on our bodies, she has to rely on a machine.

Today, kidney disease ranks fourth — after heart disease, cancer and pneumonia — and claims the lives of close to 55,000 people a year.

Now, however, there’s good news for anyone whose blood must be mechanically cleaned and restored.

It’s a new blood purifying unit developed by Dow, using a technique first created for desalting water. Slightly bigger than a flashlight, it’s filled with about 11,000 hollow fibers that look like tiny soda straws. Smaller and simpler than previous devices, it can shorten the time that patients must remain immobile.

Even though artificial, it filters much the same as a human kidney. And to anyone who needs his blood washed, that’s what counts.

At Dow, we’re concerned with more than chemistry. We’re concerned with life. And despite our imperfections, we’re determined to share its promise. Wisely.

The Dow Chemical Company, Midland, Michigan 48640.
The Chemical Engineering Department at Manhattan College has had in effect for the past five years a “design-oriented” master’s degree program geared toward those students who wish to pursue career objectives in the process industries. This is a cooperative program with industry encompassing one complete calendar year. An initial internship is provided in the form of summer employment of the students by the participating companies involved in the program. The subsequent two-semester academic phase entails an intensive effort in applying fundamental engineering principles to the solution of industrial problems.

A total of thirty credits are necessary for the Master of Engineering (ChE) degree, eighteen of which are in required courses in mass transfer, fluid mechanics and heat transfer, kinetics and reactor design, and process evaluation and plant design. A prime requirement for the completion of the program is the submission of a Project Evaluation Report summarizing a comprehensive process and plant design project. The course, Process and Plant Design Project, serves as the vehicle for guiding the student through the many phases of the project including initiation, assessment of processing alternatives, design and specification of equipment, and economic evaluation.

OBJECTIVES

The OVERALL OBJECTIVE of the project is to unify and build upon a diversity of scientific and engineering principles by application to a comprehensive, open-ended problem. Specific objectives of the course are to develop the capabilities of the student in the area of process synthesis, technical and economic evaluation of alternatives, process optimization and communication skills.

The comprehensive nature of the project requires that a diversity of subjects be employed. Integration of these subjects to solve a single problem requires a thorough understanding not only of a specific area but also of its interrelationship with many other areas. Being open-ended, emphasis is placed on organizational ability to formulate a plan of attack prior to execution of any specific project detail.

The development of an overall process flowsheet based on information available in the literature or on an innovative idea involves the conceptualization of the overall problem and technical and economic evaluation of alternatives at many points in the process. Once a scheme has been developed, optimization of the entire process as a unit would be most desirable, but is usually limited to segments of the process to facilitate completion of the project during the academic phase of the program.

A salient objective of the project is the improvement of communication skills. The Project Evaluation Report is treated in the same manner as a thesis, that is, it must be both technically correct and well presented. In addition, each student must present his project orally and defend it.

ORGANIZATION

Process and Plant Design Project is offered as a three-credit course during the spring semester. However, the projects are actually selected during the fall semester. Since it is a required course, this presents no particular difficulty with regard to who will be enrolled, etc. The students normally work in teams of two; partners are selected by lot; each team works on a different project. The team approach applies only to the technical phases of process and equipment design; each individual is responsible for his or her own Project Evaluation Report. Projects can be concerned with any appropriate type of industrial design problem, but have typically involved the preparation of an organic or inorganic chemical. Some of the recent projects

* Presently participating in the program are Celanese Plastics Co., Esso Research & Engineering Co., FMC Corp., Mobil Oil Corp., Pfizer, Inc., Stauffer Chemical Co., and Texaco, Inc.
Nicholas Kafes received his BS degree at the Massachusetts Institute of Technology and his PhD at Lehigh University. He joined the faculty of Manhattan College in 1970. He has a background of over 10 years experience with The Lummus Company, a major engineering construction firm specializing in the erection of petroleum/petrochemical processing plants, and has held positions as a process design engineer, startup engineer and process research engineer. (right photo)

Edward G. Kelleher received his BChE from Manhattan College and MS and EngScD degrees from Columbia University. He has worked with Celanese Plastics Company and American Cyanamid Company, and is currently associated with Ecolotrol, Inc. in process design for environmental control. His teaching interests include mass transfer, process and plant design, and numerical methods. He is a member of AIChE, ACS, Sigma Xi, and ASEE. (left photo)

were process designs for the synthesis of urea, terephthalic acid, isoprene, vinyl chloride, and vinyl acetate from basic raw materials.

Early selection of the project enables the students to complete their literature search during the first semester. During this period, teams usually complete a preliminary process flowsheet, preliminary material balance, and a set of processing alternatives to be evaluated. Although no formal classes are held, groups meet informally with their project advisor to discuss progress.

Coordination among the graduate faculty provides the students with the background necessary to make marked progress during the fall semester. In particular, the Kinetics and Reactor Design and Process Evaluation and Plant Design courses are organized so as to provide direct input to the development of the project. The latter part of the Kinetics and Reactor Design course, which is given in the first semester, includes several case studies in reactor design. At least one of these is extended to include the development of a down-stream processing scheme and the effects thereon of varying reaction conditions. The two-semester course in Process Evaluation and Plant Design emphasizes the integrative case study approach to develop in the students the concepts of process synthesis, evaluation of alternatives, economic evaluation, and optimization. Typical case studies covered in depth in this sequence include hydrogen reforming, ammonia synthesis, nylon-6 synthesis, power recovery cycles, and hydrocarbon separation schemes.

In addition to the supplementary material given in the aforementioned courses, the background of the students is further reinforced by a seminar series that is an integral part of the overall program. The companies participating in the program provide the speakers for these seminars on topics of industrial importance. Recent seminar titles illustrating their contributive role include:

- Selection and Design of Commercial Fractionation Equipment
- Non-Linear Matrix Algebra and Engineering Application
- Profitability and Engineering Projects
- Implementation of a First Level Process Computer
- Process Modeling in Chemical Engineering
- Catalytic Reforming
- Materials Engineering in the Petroleum Industry

The project course itself is offered as a two lecture hour course with a two hour discussion period. The lecture period topics are selected to augment the material presented in basic courses, providing the student with a fundamental understanding of several areas which are important considerations for any overall industrial problem. These include:

1. Equipment design and specification
2. Safety
3. Control
4. Plant layout
5. Offsites
6. Process economics
7. Technical writing

Equipment design is limited to major specifications and does not include detailed mechanical design. Safety is considered from the viewpoint of safety in equipment design and safety in an overall processing scheme. Control schemes, rather than instrumentation, are discussed for individual units and overall segments of a process. Process economics includes estimation techniques for total capital investment, total product cost, profitability parameters, and evaluation of alternatives. Several lectures are devoted to the basic principles of improved technical writing.
skills.

The discussion period has no fixed format, but is usually devoted to a discussion of common technical problems among the groups or to discussion with the individual groups. In addition to these formal meetings, groups meet regularly on an informal basis with their project advisor to discuss problems, review progress, and plan. These informal discussions are not limited to their project advisor. The groups are free to and do consult with all members of the faculty who have a diversity of backgrounds, experience, and interests.

It is difficult to illustrate the depth to which the various phases of the project are carried, but the Table of Contents from one of last year's Project Evaluation Reports is given in Table I as a general guide. The process flowsheet includes all equipment, a complete material balance, and all major controls. The cost estimates are all based on the cost of the equipment. All equipment must be sized and reasonable details given, but without mechanical details. Specifications include all materials of construction and costs for each item.

**TABLE I. Table of Contents**

I. Summary  
II. Introduction  
III. Presentation  
   A. Description of Process  
   a. Chemistry of Process  
   b. Special Features and Innovations  
   c. Process Description  
   d. Process Flowsheet  
   B. Description of Major Equipment  
   C. Plant Layout and Location  
D. Economics of Process  
   a. Cost of Equipment  
   b. Estimated Capital Investment  
   c. Total Product Cost and Profit  
   d. Depreciation  
   e. Profitability  
E. Conclusions and Recommendations  
IV. Discussion  
V. Nomenclature  
VI. Bibliography  
VII. Appendix  
   A. Properties of Materials  
   B. Design Data  
   C. Sample Calculations  
   D. Long Tables and Computer Programs  
   E. Equipment Specifications

**DISCUSSION**

The present role of the overall program seems particularly important in enabling students to make the transition from the classroom to an industrial environment. Judging by the input from industrial representatives, it has been particularly effective in improving the competence of young engineers by affording them an intensive, guided experience in developing their capabilities in handling industrial problems.

The students have found that the comprehensive nature of the process and plant design project has been effective in giving them a broader perspective of chemical engineering. They have learned to think more effectively in terms of the overall result of changing a single problem variable. They are better prepared to evaluate alternatives on both technical and economic bases. They are more aware of the total implication of a single engineering decision.

The lecture material of the course contributes to this broader view of engineering. Although many of the topics are in actuality the domain of specialists in their respective fields, the students develop at least a basic working knowledge of these areas and an appreciation of their role in the overall engineering picture.

The continual interaction of the students with the faculty is conducive to the meaningful cross fertilization of ideas. Reinforced by the summer internship in industry and continued contact with practicing engineers during the seminar program, this manifests itself in realistic approaches to the solution of a given problem. Needless to say, this does require a considerable commitment in time and effort on the part of the faculty and the participating companies.

The emphasis placed on teamwork in the project has many obvious benefits. It does make the workload more reasonable and allows time for creative effort. It also leads to discussions of tremendous mutual benefit to the students as well as to some innovative ideas in processing techniques. At the same time, individual effort is required to prepare the final Project Evaluation Report. Improved communication skills result from the emphasis placed on the written presentation of the report and from the oral presentation of the project in a seminar.

Overall, student reaction to the project has been extremely favorable. Students have found it to be the unifying agent within their graduate education. This is not as much due to the fact that the project represents the culmination of the program as it is that it serves to interlace much of the knowledge previously held to be unique and isolated.
THE DOMINANT TREND in engineering education for the last 10 to 15 years has been toward engineering science. Much of the research effort has been concerned with the development of new techniques to solve technical problems, the undergraduate and graduate curricula emphasize the available methods used to describe physical systems, and the laboratory courses are used to support the theoretical material presented in the lectures by demonstrating that experimental data generally agree with theoretical predictions. Although this increased effort to develop new approaches to problem solving has led to some significant advances in technology, it has been accompanied by a de-emphasis in the search for economic solutions to real problems. In fact, economic analysis of engineering problems is generally discussed only in a senior-year design course, rather than being integrated throughout both the undergraduate and graduate programs.

With these changes occurring in engineering education we are training students to have an appreciation for the fundamental methods of engineering instead of the actual practice of engineering. Since the practice of engineering usually requires efficient, economic solutions to problems that have never been solved before, a student needs to acquire the ability to recognize how to complete the statement of a problem, how to decide on the best approach, how to determine the required accuracy of any solution he develops, and how to sell his solution either to his management or to the public. Unfortunately, many present engineering programs ignore most of these questions. After entering industry, a student often realizes that the intuitive notions he gained from his courses frequently are more valuable than the quantitative methods, that it is often more efficient to solve a problem experimentally rather than undertake a theoretical analysis, that it is much more advantageous to use a highly directed approach to get quick answers to a problem rather than a scholarly understanding in depth, etc. Thus the university needs to find ways to give engineering students an enhanced ability to perform in the real world of engineering practice.

One approach we are using to improve the balance between theory and practice at the University of Massachusetts is to introduce an elective course in entrepreneurship, described below. The purpose of this course is to get students to generate ideas that they would then translate into commercial ventures. We anticipate that most of the projects will continue to be in such areas as household items or sporting goods because the students have a better overall background in these fields than they do in the chemical industry; for example, they are better able to relate to the problems of the expected sales price and potential total sales in the development of a new ski than the development of new chemical products. Although we would prefer for a larger number of our students to focus their efforts on industrial chemistry, the advantages gained by having a student realize the balance between theory, estimation, experimentation, marketing, and sales in the quick and reliable solution of an unsolved problem seem to us to outweigh the disadvantages of deviating from a chemical orientation. Moreover, we have found that a high level of enthusiasm is generated in the students when they recognize the realism of the unsolved nature of the problem (compared to most laboratory exercises), the expected commercialization of the final product, and, of course, the necessity of the student to find the capital required to finance his venture. This capitalization requirement means that realistically we have to restrict our interests to projects having low investment costs.

To date we have offered this course on entrepreneurship on an experimental basis to a class of four “hand-picked” graduate students in a 3 credit hour course, and to eight freshmen in a 1 credit-hour course. These graduate students all had excellent grade-point averages, but very different personalities and interests. As might be expected, the student performance varied widely, and the performance seemed to correlate better
with an interest in entrepreneurship or personality characteristics than academic background. We were highly pleased with the progress and performance of both groups of students. (We are investing our time and capital in several projects for future commercialization—the most sincere grade a student can be given.) Also we plan to expand it into an option in our Master's Degree Program and to offer the material to sophomores and more advanced undergraduates as a special studies program. It is too early to assess any improvement in the ability of the students to practice chemical engineering, although we are optimistic that an enhancement of these abilities is taking place.

COURSE DESCRIPTION

In a few introductory lectures we discussed some of the recent surveys that demonstrate the decreasing competitive position of the United States in the world market, the fact that over 100,000 manufacturing jobs have been lost in Massachusetts alone in the last 5 years, and the role of engineering in improving this position. The purpose of engineering is to find ways to create new wealth, and often this is accomplished by translating scientific ideas into specific products that people will buy to make their lives more pleasant in some sense. One of the keys to the development of a new product lies in the original idea, but no idea has value unless it can be translated into a successful commercial venture. Therefore, the two main topics covered in the course were idea generation and the procedures required to develop and commercialize a new idea, termed idea exploitation.

Idea Generation

Most industrial corporations have an established organization to develop new products for the company. Normally they attempt to accomplish this goal by looking for new applications for existing company products, searching for new uses of by-product materials, hunting for new sources of raw materials, and evaluating the effects of modifying existing processes and products. The search for new opportunities is restricted to those that are in general conformity with the company's goals and past experience. On the contrary, a private inventor frequently possesses a broader range of interests in business opportunities, perhaps by finding out what frustrates people and looking for a product that will relieve that frustration, by close observation of how present devices work and then discovering a better way to do the same task, or by recognizing that a technique someone has used to solve a particular problem can also be applied to a new area. Thus a private inventor is limited only by his imagination and the extent of his knowledge. In class we presented numerous illustrations of published inventions in four categories: looking for applications of an existing body of the inventor's expertise, looking for ways to satisfy existing needs in the marketplace, looking for ways to fill "holes" in a market even though a need is not readily apparent, and looking for new applications of existing products or new ways to produce existing products.

After discussing a large number of examples of idea generation in class, we asked the students to generate some ideas of their own. We were very surprised at how well they did, and there were many more projects of potential than we had time to pursue. Similarly, the concepts of idea generation were presented in a Freshman Engineering Module (a four-week short course) and the freshmen also came up with some outstanding ideas. The students seemed to enjoy this part of the course tremendously, and it went very smoothly.

Idea Exploitation

An idea has value only if it can be translated into a commercial venture. About 59 out of 60 ideas that initially appear to be promising fail somewhere along the line, and frequently the marketing difficulties are much tougher to overcome than the technical problems. With a high potential failure rate it is necessary to find a way to screen ideas very quickly for both their technical and marketing potential, rather than to complete a lengthy technical development of a product and then find that it can't be sold. Thus the best approach to use in developing a new product is a method of successive approximations, sometimes called the engineering method, where an attempt is made to get a complete solution to the whole problem as quickly as possible by ignoring all but the most essential details of the solution; this procedure must be developed by practice in the course. If the results of this initial solution look promising, we then determine the most critical areas of the solution and attempt to fill in the details of the analysis. By using this approach of obtaining successive solutions, which are more accurate as more of the details are considered, we have the advantages of quickly dropping projects with little promise either from a technical or a marketing standpoint, of obtaining a rapid assessment of the critical areas of the development of the product, and of having a fast solution to the overall problem that we may be able to implement with an appropriate use of safety factors. Similarly, the application of the engineering method is normally the most efficient approach because even though we solve the same problem many times in varying degrees of detail, we avoid going down dead ends or wasting time in a lengthy analysis of parts of the problem that are not very important.
The purpose of engineering is to find ways to create new wealth . . . by translating scientific ideas into specific products that people will buy . . .

A useful set of questions to consider during the initial screening of a project are: Is it technically feasible? Can it be sold? Is there a significant market? Has it been done before? In answering these questions, we simultaneously consider: How difficult will it be to commercialize? What are the critical problems to be solved? Answers to these questions should be determined initially only by guestimates or by order-of-magnitude calculations. It is somewhat surprising how many projects will be dropped after spending only an hour or so thinking about these questions. Of course, part of the reason for this rapid rejection is that projects compatible with the low levels of available capital normally yield a small profit; the amount of effort required to solve the technical and marketing problems, along with the uncertainties associated with the development, often makes the project not seem to be worthwhile.

Once a project has passed the initial screening test, it is desirable to take a more formal, although still iterative, approach. After the critical stages in the development have been identified, then it is reasonable to proceed through the line presented below:

1. Complete the statement of the problem and define the critical steps of the problem
2. Translate the problem into engineering or marketing terms (costs and values)
3. Make a sketch or diagram of the system or operation
4. Use the sketch to try to guess a better answer
5. List the assumptions you need to make to undertake the simplest possible analysis of the problem
6. Estimate a solution based on the assumption in step 5
7. Evaluate if the solution is reasonable
8. Determine the effect your analysis has on your original overall solution to the problem
9. Examine the importance of the assumptions you made in step 5
10. If your analysis still leaves you with the critical item of the highest priority return to step 1. Otherwise, rerank the priorities of the critical problems and apply the procedure to the next most critical item.

The list above should be considered only as a guideline since in many cases it will be possible to skip several steps, iterations will take place within the main loop, or the steps will be rearranged into a different order. Nevertheless, the list provides a useful guide, particularly near the beginning of a course when a student tends to get bogged down in sophisticated solutions to technical problems that are similar to those he encountered in his previous course work. In fact, it is a difficult matter to get a student to use order-of-magnitude calculations, when he knows that he could get an exact solution by solving a partial differential equation, i.e., there is a tendency to substitute many hours worth of straightforward but tedious algebra for one hour of thought.

COURSE OPERATION

We were quite convinced, even with no experience in teaching this type of course, that it would not be possible to teach the practice of engineering by lectures alone; hence, the course was run as a mix of lectures and discussions of individual projects carried out by the students. The lectures were designed to be relevant to the stage of development of the individual projects and the presentations were so timed.

The initial four weeks of the semester were allocated to lectures on idea generation and the use of the engineering method in idea exploitation. During this time the students practiced “taking a problem apart” in generating about 100 ideas for exploitation in the home industry, ranging from basement finishing to the manufacture of plastic headboards for beds (the ideas need not be original, except to the students involved). The students then generated a number of ideas individually, conducted an initial screening of their ideas, and reported their results to the class. The other students in the class questioned their analysis and the class as a whole held a “directed” brainstorming session. Here we tried to reevaluate the potential of the idea, to look for avenues providing even more profitable operation, or secondary problems that could be attacked if the original one failed. Then each student chose a project and started to proceed toward the commercialization of his idea. Class periods were spent by having the students define the critical problems of the moment, to present the priorities they placed on these problems, to discuss how they used the engineering method to solve the problems, to illustrate the kinds of order-of-magnitude calculations they found to be helpful, and to describe the work they planned to pursue. A significant number of comments were offered by the remainder of the class, and the teachers used this direction as a primary vehicle for teaching the practice of engineering. The students claimed that they learned a lot about “problem solving” from this part of the course, and we feel they progressed significantly as engineers.

Of course, the students often encountered problem areas where they had no background, such as procedures for obtaining patent protection or how to start a corporation (as well as the cost of these endeavors). The students thus learned how to quickly learn specific points of information in foreign subject areas; the faculty also provided some such information in a lecture format. We
the kitchen faucet, it would be possible to relieve the problem of steam filling the room and also increase the rate of evaporation by pulling a vacuum on the system. They quickly realized that, by leading a hose from the top of the pot to an aspirator on the front yard, a jug to collect sap, it seemed to be a low cost venture to produce maple syrup by boiling off 40 parts of the sap to the one part retained as syrup. However, when Dr. Douglas returned from work every day to find the kitchen literally filled with woodwork and the wallpaper, and when two pans were allowed to boil dry and were ruined, he was convinced that there must be a better way to make maple syrup at home. Thus the students were asked "What should we do about the problem of developing a home unit to make maple syrup?"

Solution

Most students seemed interested in the problem and realized that their chemical engineering background could be helpful to them, as they envisioned problems of evaporation and level control. They quickly realized that, by leading a hose from the top of the pot to an aspirator on the kitchen faucet, it would be possible to relieve the problem of steam filling the room and also increase the rate of evaporation by pulling a vacuum on the system. Then they developed a wide variety of devices for automatically measuring either the viscosity or density of the material in the pot and turning off the stove when the end point was reached. Hearing their tentative approaches to the problem increased their interest in doing additional work, and several students proposed conducting some experiments to gather information they thought might be useful.

Cigarette Filters

In early 1972, the Surgeon-General of the U.S.P.H.S. announced that cigarette smoking had begun increasing again, and that a more effective filter must be devised if we are to protect the populace from the tars and nicotine thought to contribute to lung cancer.

From our experience in the oil industry, we realized that the tars and nicotine were simply basic aromatic compounds. Furthermore, such compounds have traditionally been removed from process streams by adsorption on high surface area solids, such as charcoal or clay. Charcoal is, of course, a component of one present cigarette filter. However, we reasoned that a high surface area solid acid, such as silica alumina or zeolite, should be even more effective. One of our students was thus assigned the task of making a preliminary evaluation of this proposal in two days, under our direction.
Solution

The obvious question relating to the marketability of a new cigarette filter is the cost of the absorbent per pack of cigarettes. Using the volume of charcoal in a Lark filter, the assumption that the new adsorbent could be used in the existing plastic cap on Doral cigarettes (or an equivalent specially manufactured cap), and the present market price for zeolites (the most expensive of the solid acids under consideration), we calculated that the incremental cost of the filter would be less than ½ cent per pack. Hence, the project was deemed to be sufficiently reasonable to define how the effectiveness of the new filters could be tested.

To determine how tars and nicotine are evaluated for cigarettes, in one day we called without success, the following:


Finally we called the Tobacco Institute Testing Laboratory, where we talked to a laboratory technician who gave us a complete discussion of the gravimetric technique used as well as literature references describing the test.

That night we looked up the Journal of the Association of Official Analytical Chemists to find the specifics of the tar and nicotine test. We found that a smoking machine is used to test 10-20 cigarettes to obtain an average tar and nicotine level. The smoke is drawn through a commercially available filter unit; a volume of 35 ml. of smoke is puffed for a duration of 2 secs, once each minute. The filter paper is weighed before and after 10-20 cigarettes are smoked, the weight gain representing total tars, nicotine and moisture. The filter paper is soaked in an isopropanol-ethanol solution for extraction of water; the water content of the solution is determined by gas chromatography. The solution is then steam distilled to remove alcohol, and the nicotine then steam distilled from the tars; the nicotine content of the distillate is measured by infrared absorption at three wavelengths. The amount of tar is obtained by difference.

It became quickly apparent that we could neither duplicate this procedure in our laboratory nor afford the expense and time delay of sending our experimental filters to an independent testing laboratory. However, in reviewing the reported magnitudes of the tar, nicotine, and water levels on the filter paper, we realized that the water represents only 20-25% of the weight gain of the filtered paper. Since we were interested in significant improvements in tar and nicotine levels (e.g., up to 90% reduction of present levels), it appeared likely that simple measurements of the total weight gain of the filtered paper would be sufficient to indicate filter performance; the involved analysis procedure could be used to confirm the performance of those filters which were superior in our simpler tests, and those detailed tests would be performed by the Tobacco Institute Testing Laboratory.

Having established that our solid acid adsorbent concept was economically feasible and that a simple and inexpensive testing program could be initiated, we next turned to the patent literature to determine if such concepts had been previously invented. Much to our chagrin, we found not only 200 patents disclosing cigarette filters but also a 1958 patent covering the use of zeolites in cigarette filters and several more recent patents improving on this idea (e.g., changes to prevent the zeolite from drying out the tobacco, to prevent the adsorption of low molecular weight aromatics contributing to taste, etc.). At this stage, after about two man-days of effort, the project was abandoned.

Even though this project was terminated after only two days, the activity was of value to the student. They had learned to rapidly define the critical steps in an investigation, to simplify complex tasks for initial screening purposes, and to rapidly assimilate information in an unfamiliar field. We suggest that these are among the diagnostic arts important to the successful practice of engineering. Other important areas, such as the methods the student would use to sell his idea to tobacco company management and the relative importance of marketing, were not covered in detail with this problem. These items are more logically pursued with other, more successful, projects.

CONCLUSIONS

Obviously it would be nice to be able to say that several projects were brought to a successful completion during the course. However, the students appreciate the fact that an actual attempt at entrepreneurship will make artificial university time schedules meaningless, and they were willing to continue their efforts throughout the summer. Similarly, it might be of interest to describe the projects that appear to have sufficient promise that we are willing to supply our own capital to finance them, but one thing an entrepreneur learns very early in the game is to never reveal promising ideas until they have been exploited and sold! Nevertheless, we hope to make some successful case studies available in the not too distant future.

COONEY (Continued from page 165)

exchange across the respiratory membrane.

For a discussion of artificial oxygenators, no suitable reference has yet been found. A chapter by Galletti in the Advances in Biomedical Engineering and Medical Physics series has been used. However, this treatment is not aimed at the novice and is not appropriate. A welcome addition to the to the biomedical literature would be a paper containing illustrations and describing the available oxygenator designs (film, disc, membrane, bubble) in simple, clear terms. The mathematical modeling of oxygenators is normally given some treatment, but not any extensive elaboration. This is an area which soon becomes complex and is best left for advanced courses.
the students construct a plastic model "Human Anatomy Kit"

TERM PROJECTS

The term projects, which may be selected by the student (the choice of topic is largely left to the student, subject to the professor's approval) in lieu of taking the final examination, have proven to be popular and interesting. Typically, they consist of ten page paper reflecting in-depth reading or analysis of some biomedical topic, or a report on an experimental investigation or on a computer study.

Last year reports were received on: experimental studies on primary perception by plants (e.g., galvanic response to distant "threats"); computer studies on countercurrent heat transfer in the leg and on artificial kidney-patient systems; and papers on biorhythms, mathematical analyses of pulsatile blood flow, and modeling the effects of anabolic steroids on the body.

ASSESSMENT OF THE COURSE

This course has been favorably received and has generally sparked the interest of the students. About half of the students sign up for the advanced course. The author's impressions of the course are several. First and foremost, as the course now stands, a large number of topics is covered in only 14 weeks and, consequently, the treatment of many topics is too superficial. After deducting from each week the time required for quiz giving, quiz discussion, homework discussion, film showing, etc. too little lecture time remains for the amount of material involved. This problem could be alleviated by shifting some topics to the follow-up course. While this would make the first course less of a survey and be disadvantageous to those students who take only the first course, some shifting is imperative.

Secondly, the course seemed a bit too qualitative to the author. Under pressure of time, many mathematical formulations were omitted and the course was overly accented towards physiology per se. By shifting some material to a second semester, this problem could be ameliorated.

A third problem, mentioned earlier, was the lack of a really suitable text. This problem will hopefully be solved by the gradual development of a complete set of handouts for the course.

CONCLUSION

The reader, especially if he teaches in the same field, may have different views as to course content. However, the present syllabus seems reasonable and appropriate for chemical engineers. Additionally, a number of important topics omitted from the first course (e.g., nerve impulse transmission, physiological control systems, etc.) are conveniently covered in a second course.

As a preparation for advanced work the course seems to be effective. Several seniors have chosen to pursue advanced work in formal biomedical programs or in medical schools, and they consider the course to have been appropriate.

To the author it is exciting to be engaged in teaching at the interface of two great disciplines. Hopefully, this paper will serve to further the institution and development of similar courses in many more chemical engineering departments than presently offer such.

REFERENCES


CHEMICAL ENGINEERING EDUCATION
Over half the towns in the United States are forced to dump their wastewater in our rivers. The reason is sad.

Money. Literally over half our towns haven't got enough money to build complete wastewater treatment plants.

And many towns that have complete plants aren't cleaning the water thoroughly because the towns have outgrown the plants. And they can't afford to expand.

So, because of money, towns are forced into polluting our streams and rivers.

Union Carbide has discovered a new wastewater system that costs less. It's called the Unox System. It's the first substantial change in wastewater treatment in thirty years.

Instead of the conventional aeration system that cleans water by mixing it with the air, Unox forces pure oxygen into a series of closed treatment tanks. This forced oxygen technique cleans wastewater in less time, less space and reduces the total cost up to forty percent.

It means a town can boost its wastewater system by simply adapting the Unox System to the existing system. And towns with limited means can now afford a complete system.

A number of cities and industries throughout the country have already chosen the Unox System. And more installations are being planned.

We've discovered a cheaper way to treat wastewater because our streams and rivers can't afford to wait.

For additional information on our activities, write to Union Carbide Corporation, Department of University Relations, 270 Park Avenue, New York, New York 10017. An equal opportunity employer.

This book emphasizes the bare skeleton of transport phenomena. It teaches the systematic formulation and solution of boundary value problems involving momentum, energy, and mass transfer, and combinations of the same, in solids, and in liquids in laminar flow. The coverage includes chemical reactions involving heat effects.

A student who studies this book will become proficient in setting up transport phenomena boundary value problems. He will have an opportunity to apply his mathematical tools: Leibnitz rule for differentiating integrals, Gauss’ divergence theorem, separation of variables and Laplace transform methods for solving partial differential equations, properties of Bessel functions and the error function, Runge-Kutta and finite difference methods for solving ordinary and partial differential equations. He will develop insight into the physical significance of the pertinent partial differential equations. Chapter 2 provides some mathematical tools. Chapters 3, 4, 5, and 6 are the meat of the course.

In Chapter 2, the author teaches the fundamentals of vector analysis. In chapters 3, 4, 5 he derives the equations of continuity, motion, energy, and mass transfer. He uses the vector method and a stationary volume element. In each of these chapters he tabulates the equations in rectangular, cylindrical, and spherical coordinates. He assumes all physical properties are constants. He restricts discussion to binary mixtures. He uses a simplified form of Fick’s law.

In sections 3.6, 4.6, 5.6, 6.3, and 6.5 he teaches by presenting a series of well planned examples. These show the student how to “extract” the equations for a particular case from the tables of general equations, how to choose appropriate boundary and initial conditions, and how to solve a boundary value problem after it has been formulated. He emphasizes systematic procedures. The examples are stimulating. Most are adapted for self study. A few are specially suited for in-class discussions. Problems at the ends of chapters 3, 4, 5, 6 give the student a chance to drill. These problems also are well planned and stimulating, and are not overly difficult.

In most part the author writes unusually well. He helps his reader proceed rapidly by leaving in the intermediate steps. And he encourages the student to participate in the thought process. The format of the book is conducive to study. The print is large. Bold face type effectively sets off chapters, sections, examples, figures, and tables. Equations and text are nicely spaced out. Figures are numerous and well drawn. The page size, type, and format are reminiscent of Transport Phenomena by Bird, Stewart, and Lightfoot, John Wiley and Sons, publisher.

Most of the nomenclature is consistent with that of Transport Phenomena by Bird, Stewart, and Lightfoot. There are some differences. For example:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{df}{dr} )</td>
<td>L(^2) differential surface element, p. 40.</td>
</tr>
<tr>
<td>( \frac{d\tau}{L^3} )</td>
<td>differential volume element, p. 45.</td>
</tr>
<tr>
<td>( P_m )</td>
<td>pounds moles , p. 191.</td>
</tr>
</tbody>
</table>

\(<Q>\) of \( Q \) time average of \( Q \) in turbulent flow, p. 58.

To supplement this book the student will need a table of Laplace transforms, a handbook of numerical tables of functions, and Dwight’s Tables of Integrals and Other Mathematical Data, the MacMillan Company, publisher.

Some observations and suggestions:

The author uses Liebnitz rule many times, but he does not include this rule in his chapter 2 on mathematical preliminaries. On pages 78, 84, 145, 203 he applies the rule implicitly. The author does a good job of deriving the equation of change by the vector method. Some students will ask about \( r \cdot df \), p. 83 and will question the Gauss type divergence theorem, p. 85. More mathematics in chapter 2 would take care of such questions.

The reviewer feels that the shell balance method is the least ambiguous method for deriving the equations of change. There are only two examples of shell balances in the book, see index. Both are confusing. A more explicit explanation of the sign convention for \( \tau \) would help. The author uses a simplified form of Fick’s law. The reference velocity for the mass flux vectors \( J_A \) and \( J_A \) pp. 193-195 is not clear.

This book is a text not a handbook. Nevertheless it contains considerable useful reference material. A list of the tables would provide a convenient index to this material. A concise summary of the examples and their solutions is tabulated pp. 247-251. There are 50 problems total at the ends of chapters 3, 4, 5, 6.
This book "evolved from notes prepared by the author for a required one-semester three-credit course given to senior chemical engineering students . . . The course is offered as an elective to other engineering disciplines . . ." The book has been pared down to the bone. Prediction of transport properties, shell balances, turbulence, convective coefficients, and macroscopic balances are discussed very briefly or not at all. Even the bibliography has been omitted. The author depends on the teacher to provide embellishments.

The drastic abbreviation in content adapts the book to special applications. Foremost is that of text for a 3 credit senior course like that the author teaches. All three transport phenomena can be covered in a single semester. Ideally such a course would be preceded by a more traditional two course sequence in momentum, energy, and mass transfer. The senior course would then fix the structure of transport phenomena in mind and stimulate interest in applications and advanced study. This book would be useful as the text for a refresher course for practicing engineers. For this purpose the current edition of Transport Phenomena, by Bird, Stewart, and Lightfoot would be a good companion volume.

J. Lloyd Sutterby
University of Missouri-Columbia

NEWS (Continued from page 152)

interaction with industry, information about new textbooks being written or evaluated etc. A third objective is to interject into the whole educational system the exciting and new experiments and ideas that are being done.

The format of the minisession is unique. From the responses to a questionnaire circulated in June, some will be selected to briefly describe the unique features and challenges in presenting this material. These will be very brief, say 2 to 10 minutes, with the main purpose being to introduce people and ideas. The meeting may break up into smaller buzz sessions or group discussions; again the main purpose is for everyone to get to know each other and to have some idea of what everyone is doing. Available at the back of the room will be copies of course descriptions, hopefully from each and every school. We may also have sample textbooks or manuscripts on display. After the formal session, we then adjourn to have lunch together (in groups of 6 to 10) in various locations so that the discussion can continue informally.

The minisession forms part of the "Free Forum on Undergraduate Education" with G. F. Bennett, University of Connecticut, Co-Chairman. The minisession is co-chaired by D. R. Woods, McMaster University, Hamilton, M. J. Gluckman, City University of New York and Drs. Bennett and Howard. For more information contact: D. R. Woods, McMaster University, Hamilton, Ontario, Canada. 416-522-4971 Ext. 292, or G. F. Bennett, University of Toledo, Toledo, Ohio 43606.

ANNOUNCEMENT

The Latin American Teaching Fellowships program is now accepting applications for positions in Latin America from individuals in the social and natural sciences, engineering, business, law, and medicine who hold PhD's, professional degrees, or are PhD candidates. Placement possibilities exist for the 1973-74 academic year. These opportunities are part of a service program to assist Latin American universities to develop advanced programs. Salaries are geared to moderate subsistence level rather than being competitive with North American salaries. Address inquiries to Latin American Teaching Fellowships, Fletcher School of Law and Diplomacy, Tufts University, Medford, Massachusetts 02155

To AIChE Members:

CHEMICAL ENGINEERING EDUCATION is now available to AIChE members at a special rate of $6/yr. Please send your remittance to R. B. Bennett, Business Manager, CEE Department of Chemical Engineering University of Florida Gainesville, Florida 32601

TO DEPARTMENT CHAIRMEN:

The staff of CHEMICAL ENGINEERING EDUCATION wishes to thank the 55 departments whose advertisements appear in this fourth graduate issue. We also appreciate the excellent response you gave to our request for names of prospective authors. We regret that, because of space limitations, we were not able to include some outstanding papers and that certain areas are not represented. In part our selection of papers was based on a desire to complement this issue with those of 1969, 1970 and 1971. As indicated in our letter we are sending automatically to each department for distribution to seniors interested in graduate school at least sufficient free copies of this issue for 20% of the number of bachelor's degrees reported in "ChE Faculties." Because there was a large response to our offer in that letter to supply copies above this basic allocation, we were not able to fully honor all such requests. However, if you have definite need for more copies than you received, we may be able to furnish these if you write us. We also still have some copies of previous Fall issues available.

We would like to thank the departments not only for their support of CEE through advertising, but also through bulk subscriptions. We hope that you will be able to continue or increase your support next year.

Ray Fahien
Editor
Mack Tyner
Associate Editor
R. B. Bennett
Business Manager
Graduate education in chemical engineering has been offered at Loughborough for over 20 years, but in the last few years major changes have occurred, so that the present courses bear little relationship to what went before. We are not writing here about changes in subject matter or course content, as these will change naturally with the development of the subjects and with the interests of the faculty members who teach them, but rather about changes in the institution itself and in the Department's philosophy. Since these changes have had a significant effect on the shape of the present graduate courses, it seems sensible to outline them in order to give a background against which to see the present structure.

BACKGROUND

Although the College is over 70 years old and has a history of courses in chemical engineering for 50 of these years, it only became a University, i.e., in U.K. parlance a degree-granting institution, in 1966. Since that time it has offered both M.Sc.'s and Ph.D.'s in chemical engineering, although prior to this graduate studies were carried out in which candidates worked for the degrees of external bodies. These changes in status were accompanied by rapid growth in size and it is only natural therefore that there should have been a very marked evolution in graduate work. In all this a general pattern has been followed—graduate courses had their beginnings in specialist subjects which were the interests of faculty members and on which they were doing research and then expanded so that now we have a graduate course which is broadly based and general for the first four months and then splits up into a number of options, allowing students to study some subject area in greater depth.

This course pattern reflects to some extent the undergraduate course in which the first two years are spent in general chemical engineering training followed by a final year in which students select four or five subjects out of a possible 8, and study these in depth. Four different courses are offered at undergraduate level. These are

- Chemical Engineering (4 years)
- Chemical Engineering (3 years)
- Chemical Engineering and Management (4 years)
- Chemical Engineering and Polymer Technology (4 years)

The last three of these are new and to that extent experimental. The four-year courses include a period of industrial training which occupies the whole of the third year.

The undergraduate courses are thus becoming increasingly modular in nature. Nor is this situation confined to the universities. There is a considerable educational ferment going on in British schools. So far we have been able to assume a considerable degree of uniformity in the educational background of students entering our undergraduate courses, qualifications in mathematics, physics and chemistry being normal. Now, not only is there a growth in less usual combinations of subjects, but the content of, say, a mathematics course may vary widely. Some students will have done a good deal of matrix and linear programming work, others virtually...
D. C. Freshwater is Professor and Head of Department of Chemical Engineering. He graduated in chemistry at Birmingham and then worked in industry for a number of years before returning to University to take a PhD in Chemical Engineering. His research interests include mass transfer, equipment design and filtration and he is a founder member of INCOFILT. He has presented papers at several AIChE annual meetings and is currently editor of the Chemical Engineering Journal.

F. P. Lees is Senior Lecturer in the Department of Chemical Engineering. He received a BSc and a PhD in Chemical Engineering respectively at Imperial College, London in 1959 and at Loughborough in 1967. He worked in the steel industry for two years and in Imperial Chemical Industries for 11 years. His research interests are process modelling, computer control, human operator control, and reliability engineering. (right photo)

none. This obliges us increasingly to tailor study programmes to the individual student.

The fact that most of our own graduates have some industrial experience we regard as a considerable advantage. Six or seven years of academic studies without industrial application is not really an ideal training for an engineer.

In describing the graduate education at Loughborough, many differences will become apparent between what we do and common practice in the United States. Some of these are peculiar to our approach at this institution, others are inherent in the British system, two features of which should be explained. The first is that teaching in both undergraduate and graduate courses consists of three academic terms of ten weeks each, beginning in early October, with breaks of about 3 weeks at Christmas and 3 weeks at Easter, and ending in June. The second is that it is possible in most British universities to work for a Ph.D. without any formal requirement to undertake course work. In fact Loughborough is probably unique amongst U.K. chemical engineering departments in its requirement, which was instituted two years ago, that all doctoral students should have first completed a master's degree by course work. Once this course work requirement is fulfilled, however, no further course work is required of the doctoral student, although he may attend appropriate courses of his own volition.

**PURPOSE OF GRADUATE EDUCATION**

In developing a formal course of education it is necessary to have some ideas of the purpose of the course. We regard the aim of the master's course as being to give the students a broad training in what we see as some of the mainstream areas of chemical engineering at a level higher than that which can be reached in the normal undergraduate course, followed by in-depth study of a selected subject area, involving both book work and project work. The doctoral training we see as complementing this by providing firstly a training in research methods and secondly an opportunity to demonstrate a capacity for original thought.

**THE MASTER'S COURSE**

There are in the department four main research groups. This is reflected in the four specialist options offered within the Master's course. These are:

- Chemical Systems Engineering
- Particle Technology
- Process Engineering and Economics
- Transfer Processes

The course is of twelve months' duration and consists of three parts, as shown in Table I. Part I is a common core, which is taken in the first two terms. Part II consist of the option subjects, which are selected from those shown in Part II of the table in accordance with the option chosen. These are taken mainly in the second and third terms. Many of the subjects listed are covered, of course, at undergraduate level, but the content on the Master's course is more advanced. Part III is a project, in the subject area of the option taken, which starts at a low level in the second term and is than pursued full-time from the end of June through the summer. There are written examinations at the end of the second and third terms and oral examinations at the end of the second term and of the course.

The largest research group in the department is that of particle technology. The activities of
it is possible in most British universities to work for a Ph.D. without any formal requirement to take course work. In fact Loughborough is probably unique amongst U. K. chemical engineering departments in its requirement ... that all doctoral students should have first completed a master's degree in course work.

this group cover the whole range of particulate systems, including particle characterisation, particle production, particle-fluid and particle-particle systems. The process dynamics and control group is concerned with mixing theory, process modelling, estimation theory, computer control, human operator control and reliability engineering rather than control theory. The process technology group has interests in process economics and in reaction engineering. The transfer processes group works in the area of fluid flow and heat and mass transfer. Although these groups are convenient and effective as a means of organising both research and teaching, there is nothing rigid about them, and many individuals have a foot in two camps.

The Master's course is built around these research groups. A certain number of contact hours are time-tabled for each subject and the lecturer concerned is left free to use these as he thinks fit. Usually about half the time is devoted to formal lectures and the other half to tutorials. Unlike many American courses, lecture courses are not built around a particular textbook but represent a re-distillation of the lecturer's reading and his own original work in the subject area.

The number of students on the course is of the order of 15-20. About half of these will terminate their studies after taking their M.Sc. and about half will go on to doctoral studies. The object of requiring prospective Ph.D. students to take the M.Sc. course is to give them a more thorough training in their specialist area. Although we regarded this as worthwhile in its own right, we did expect to have to pay some penalty in that the time available for the doctoral thesis itself would be less. It is perhaps too early to be sure, but it is our impression that this is compensated by the students' increased effectiveness due to their Master's training.

THE DOCTOR'S COURSE

After completing the M.Sc. students who are considered suitable and who wish to do so, go on to take a Ph.D., working usually in the same subject area, though not necessarily on the same precise topic. There are no pre-doctoral tests other than the Master's examination and the student is expected to work on his chosen topic and to present a thesis on this, normally within two years after taking his M.Sc.

LOUGHBOROUGH - GEORGIA TECH COURSE

As a result of the Department's activities in particle technology, links have developed with other centres with similar interests. One of these is Georgia Institute of Technology and we now run a joint Master's course in particle technology with this Institute. At the Loughborough end this is based on the particle technology option within the M.Sc. course. There is an exchange of students, six months being spent in each institution. This scheme is now in its second year and we are anxious to see it develop.
FINANCIAL SUPPORT

Most of the financial support for graduate work in the U.K. comes from the Government via the Science Research Council, which is roughly analogous to the N.S.F. This body provides studentships both for graduate courses and for Ph.D. work. It also awards research contracts, although students are not normally supported in this way. Another source of support for students is research contracts from industry. At Loughborough over the past few years about half our Ph.D. students have been supported in this way. The research grants are nicely calculated to cover the student's bare living costs and pay his fees.

THE U.S. GRADUATE

Through frequent visits to the United States and also through our exchange with Georgia Institute of Technology, we have learnt of some of the problems which British graduates have when they go to do graduate work in the United States and of those which American graduates encounter here. The biggest problem our students find across the water is not the difficulty but the sheer volume of the work which they are expected to do. It is our impression, gained both from first-hand experience and from talking to students, that the quantity of work set in the average Master's degree in the United States is so great as to make it rather difficult for the student to take time off to pursue subjects on his own and to appreciate intelligently just what he is doing in an overall sense. On the other hand, since we do not have the coursework system with "homework" having to be regularly handed in and marked, American students who come here find themselves very much at a loss for the first week or two. They are not used to our system which assumes that the student knows how to work for long periods on his own and which only covers in lectures a relatively few important topics. However, we have found that those students from the United States who have come to us have settled down quickly and progressed well. Both systems evidently have their merits. We prefer our own, but often find the results of the American system impressive.

TRENDS: (Continued from page 149)

\[
\hat{y} = 77.8 \pm 1.3 - 6.088(x(2) - 1.3) - 5.21 \log(x(2) - 5.2)
\]

where

\[
y = \text{average grade, estimated by Eq. (2)},
\]

\[
x(1) = \text{time in years based on zero time in May 1961},
\]

\[
x(2) = \text{time in residence, in years, prior to taking the examination}.
\]

The line represented by Equation (2), at an average experience such that \(x(2) = 1.31\), is shown in Figure 3. Of the 35 data points available, only those for which \(x = 1.3\) are included.

Figure 3 — Final Computed Average Grade vs. Date and Experimental Points.

On the basis of these results, the department has concluded that, in the period from May 1961 through May 1971:

1. There was a definite tendency for the grades to decrease and that this tendency accelerated in the later part of the period.

2. There was an apparent disadvantage in prolonging the time in residence before standing for the examination, the reason for which is not clear but the evidence therefore being incontrovertible from this analysis of the data.

3. None of the lowering of the grades in the later years of the period studied can be attributed to an increase in the proportion of foreign students, with potentially concurrent language and communication problems.

4. A correction should be made for the obviously increased difficulties which the faculty had suspected were progressively being built into the examinations; suitable action was taken in October 1971 with a gratifying improvement in the average grade of the eleven students who presented themselves for the examination.

J. C. Whitwell
L. Lapidus
Princeton University
A PLAN FOR GRADUATE STUDENT RESEARCH IN ENGINEERING

JAMES A. NEWMAN
University of Ottawa
Ottawa, Ontario

IT IS THE AUTHOR'S opinion that a great many graduate students in engineering research fail to achieve their desired objectives in an efficient manner because of poor planning and lack of foresight.

One approach to the solution of complex problems is that of systems engineering and it would seem logical, because of its success in so many other areas, to extend its use to the design of a graduate research program. The purpose of this article is to attempt to show how this process could be systematized and to indicate to the student how he might conduct his research program with greater success than that generally achieved.

A system, in general, can be envisaged to consist of five major components; a process, inputs and outputs of the process, feedback and evaluation. A model of the proposed system which incorporates all of the above elements is shown in the figure. Five separate overall phases can be identified: 1. problem formulation; 2. design; 3. production; 4. operation; and 5. completion.

It is not suggested that this scheme is the only one that could be envisaged; nor is it expected to cover every possible contingency. No doubt such a plan does not account for every possible situation that might arise. It does however represent an outline with which a graduate student could organize his research program and does provide guidelines along which the research can proceed.

PHASE I PROBLEM FORMULATION

The student, at the beginning of his research, will usually find himself with what appears to be a rather vaguely defined problem (e.g., "A Study of the Behaviour of . . ." or "An Investigation of . . ."). This vagueness will prevail since at this point the student and his advisor can seldom formulate the research topic in terms of simple explicit questions. The purpose of Phase I is to help overcome this difficulty.

The needs analysis is essentially a critical look at the overall situation with a view to identifying a specific research problem, i.e., an engineering statement of the project. Relevant factors affecting this process, i.e., inputs, include various aspects of the student's character, that of the research advisor and of the University itself.

This analysis will yield two specific outputs. These are, a desired course work program and the definition of a general area in which to perform the literature survey.

The course work program cannot (and should not) be dictated solely by the nature of the research project. However, since one major function of course work is to prepare the student to solve his research problem, the course work program must have some definite relation to the anticipated research activities.

Fig. 1. Model of proposed system.
J. A. Newman has taught mechanical engineering at University of Ottawa since 1969. He has BASc and PhD ('69) from University of Waterloo and MSE from Princeton all in mechanical engineering or aerospace and mechanical sciences.

Commensurate with the course work, the student should conduct an extensive literature survey. This point cannot be overemphasized. If the student is ever to get a clear picture of what needs to be done, he must be familiar with what has already been done.

Like the course work (which is evaluated by examinations), the literature survey itself should be evaluated. It is important, when attempting to formulate a problem, to be sure that the literature survey is complete (within reason) and that the student has a fairly good comprehension of the pertinent related research material. It is not uncommon for students to spend a great deal of time trying to solve problems which are either unsolvable or have already been solved. The evaluation of the literature survey should be conducted by the student and his advisor on a fairly regular basis throughout Phase I.

The graduate course work together with the literature survey should eventually lead to a crystallization of the specifics of the research problem and hence to a relatively clear engineering statement of the project. This becomes the major input to Phase II.

**PHASE II DESIGN**

This phase of the process represents the first step toward finding a solution to the problem previously formulated.

Generally speaking the research activity will call for both theoretical and experimental analysis. The relative importance of each will of course depend on the previous activities. One can loosely describe three different kinds of relationships between experiment and theory and it is helpful if the student recognizes them at this stage. They are:

1. An experimental analysis to confirm or deny some previously documented theoretical analysis.
2. A theoretical analysis to be performed to ascertain the important parameters responsible for a particular observed behaviour. (More often than not this observation has been made by the research advisor in some prior experimental work).
3. Experiment and theory are developed simultaneously, one complementing the other in an attempt to a) learn the important parameters and observe a real system's behaviour and b) to predict system behaviour both within and outside of the range of experimental analysis.

The first approach has one serious pitfall in that the student can attempt to design the experiment to confirm (or deny) the predictions of a theoretical model which (due to various assumptions and approximations) is in itself far removed from reality. Hence the experiment becomes the representation of a fictitious situation and the subsequent experimental results can serve very little practical purpose. The second approach above has the inherent drawback that the student himself, in an attempt to explain an observed phenomenon, can become enveloped in the fog of his theoretical hand-waving and risks losing sight of the actual physical system under consideration.

Assuming approach (3) is utilized the Design Phase should entail the simultaneous development of appropriate experimental and theoretical models. Let us consider each of these activities separately to establish the important inputs and outputs of each of the sub-processes.

Exactly what patterns of behaviour the experiment must be capable of illustrating should be relatively well established from Phase I. A successful design must have as inputs the pertinent technical information from equipment suppliers and a certain amount (the more, the better) of that somewhat elusive property, creativity. Both of these are essential to a good experimental design. At the same time, a dialogue must be established and maintained between the student and technical support staff. All too often a poor design is the result of the student's inability to comprehend the difficulties associated with the construction and operation of the experimental equipment. This results from the common lack of exposure that graduate students have had to the "nuts and bolts" world of practical engineering. The experience of the machinist, the tech-
A methodology for research does exist and the scheme described herein represents a useful and valid approach to this problem.

Also important to the above activity is the interchange of ideas between the student and other students working in similar fields. The greatest contribution that these colleagues may make however will usually be in the area of the theoretical model proposals. Other students do not have as clear a picture of the aims and purposes of the experimental analysis and hence can usually contribute little to the design of the experiment. However the basic laws of nature as represented by the usual mathematical symbols should be reasonably well understood by all involved in research. In this case it is not unlikely that other students may be able to suggest possible approaches to the structuring of the theoretical model.

The theoretical model proposal at this stage is really no more than an attempt to define the pertinent equations, assumptions, approximations, etc., that are necessary or required. In this regard a vital input is the student's mathematical insight. This is much akin to the creativity input of the experimental design process. Both of these properties are rather intangible and will vary radically depending on the particular student's abilities.

As with any other process there must be an evaluation phase. When the student and his advisor are reasonably confident of their efforts, an evaluation should be conducted by some committee. The composition of this committee is a matter for each particular institute to decide, but would usually include two or three faculty members and perhaps even one or two students whose activities are aligned with those of the student and his advisor.

A written proposal of the aims and purposes of the research along with the experimental design and the suggested theoretical approaches should be presented to the committee for study and evaluation. The committee should look for shortcomings, apparent hurdles and errors in analysis or judgment. It should then make suggestions accordingly. The outcome of this evaluation will be suggested modifications to the experimental design and possible guidance to the solution of the theoretical model.

Following this, the student is ready to enter the next phase.

**PHASE III PRODUCTION**

After consideration of the recommended design modifications, the construction of the experimental equipment can be undertaken. Much of this construction will often be performed to a large extent by persons other than the student (i.e., machinists, electronics technicians, etc.). As a result he will find some time available. However instead of continuing to develop the theoretical model, the student can receive a great deal of satisfaction in beginning to prepare his thesis. At this point many of the figures can be drawn (especially those pertaining to the experimental apparatus) and at least a good portion of the introduction can be completed. In addition to the fact that this procedure is time-saving, it provides something of a welcome relief from the intense activities leading up to the committee evaluation of Phase II.

The length of time required for Phase III will depend of course on the complexity of the experimental design, the availability of machinists, drafting facilities and so on. The evaluations shown in the figure should be conducted by the student and his advisor and may entail the building of prototype equipment, the running of preliminary experiments to check-out the apparatus, the modification of figures and write-up etc.

At the end of this production phase, the student should be ready to enter Phase IV.

**PHASE IV OPERATION**

It is this phase of the overall process that will yield answers to the research problem. Most of the activities here will be conducted solely by the student since, to be sure, he will know more about the research project than anyone else. The performing of the experiments and attempting to solve the theoretical model become a rather private affair. The dialogue between the student and advisor will be primarily a transfer of information from the student to the advisor relating the progress of the research.

The experimental and theoretical analyses are indicated in the figure as a single process even though, of course, they can hardly be conducted simultaneously. Nevertheless, both must be conducted at regular intervals (i.e., a test program followed by theoretical analysis follow-
A system can be envisaged to consist of five major components: a process, inputs and outputs of the process, feedback and evaluation. Undoubtedly, the completion of any one sub-process will indicate to a certain extent the subsequent sub-process.

The inputs to this process include the student's skills and attitudes, the availability of computational facilities for data reduction, curve-fitting etc., and other equipment and facilities (e.g., chemistry laboratory, darkroom, maintenance equipment etc.).

As with all other processes there will be an evaluation stage. During this time the experimental data is compared with existing data and with the predictions of the theoretical analysis. Modifications to the experimental test program can thence result. Similarly the theoretical data is evaluated in terms of required accuracy, range of variables considered and is compared with the experimental observations. The evaluation here could lead to a modification of the analytical techniques and a relaxation or tightening-up of certain approximations.

Eventually, after perhaps several trips around the feedback loops, there will be compiled a complete set of research results that satisfied the problem initially formulated in Phase I. This is however, not the end of the graduate student's activities. The information collected in Phase IV is of little value until it is transmitted to others. This is normally accomplished by the writing of a report or thesis.

**PHASE V COMPLETION**

Of all the graduate student's activities, this one tends to be the most tedious. The excitement of discovery is over. There remain the rather mundane tasks of preparing assorted graphs, tables and drawings and in the seemingly endless writing and rewriting of text.

Throughout its production, the thesis will be constantly evaluated in terms of its accuracy, clarity, and completeness. After a period of time (usually much longer than anticipated), the thesis will be completed to the satisfaction of the student and his advisor. It will, at that time, usually be subjected to the further scrutiny of other readers and quite possibly further changes could result. In addition an oral defense of the thesis will normally take place.

The thesis, the output of Phase V, is in fact the physical satisfaction of the need first considered in Phase I.

**CONCLUSIONS**

In an attempt to make graduate students aware of the various aspects of a graduate research program and to enable such students to cope with them in an efficient manner, a formal systematic procedure for graduate research has been suggested. This plan is felt to be applicable to most situations. Deviations from it can be conceived; however, they would in general be a reflection of an individual's inability to adhere to a formal logical systematic plan for research. It is the writer's contention that, like the design process itself, a methodology for research does exist and that the scheme described herein represents a useful and valid approach to this problem.

**SLATTERY** (Continued from page 176)

ing or developing courses in momentum, energy, and mass transfer, are faced with unchanging alternatives: survey or in-depth study? I will agree with you if you maintain that every course is a survey. But I will also insist that we do have more of a choice here than is commonly apparent in most areas.

Years ago, there was not much of a decision to be made. It was essential that a student have an in-depth understanding of piping design, heat exchanger design, and (distillation, extraction, absorption) column design, since nearly all of our students went into either petroleum refineries or the large-scale production of chemical intermediates. While these are still very useful skills to have at one's command, they are not sufficient for the wide variety of industries that are becoming possibilities for employment.

The beginning graduate sequence that I have been discussing here is a survey of momentum, energy, and mass transfer. By no means can you tell a student everything that is important to know in two or three quarters. My aim in teaching these courses is to fill in some of the more glaring holes that are of necessity left by a typical undergraduate sequence and to give a student a good foundation upon which to grow, no matter whether he is thinking in terms of a terminal M.S. or Ph.D. degree.
UNIVERSITY OF ALBERTA
EDMONTON, ALBERTA, CANADA

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Chairman
Department of Chemical and Petroleum Engineering
University of Alberta
Edmonton, Alberta, Canada

Faculty and Research Interests
I. G. Dalla Lana, Ph.D. (Minnesota): Kinetics, Heterogeneous Catalysis.
F. A. Seyer, Ph.D. (Delaware): Turbulent Flow, Rheology of Complex Fluids.
S. E. Wanke, Ph.D. (California-Davis): Catalysis, Kinetics.

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CHEMICAL ENGINEERING EDUCATION
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.

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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, 1973.

FACULTY IN CHEMICAL ENGINEERING

WILLIAM H. CORCORAN, Professor and Vice-President for Institute Relations
Ph.D. (1948), California Institute of Technology
Kinetics and catalysis; plasma chemistry; biomedical engineering; air and water quality.

SHELDON K. FRIEDLANDER, Professor
Ph.D. (1954), University of Illinois
Aerosol chemistry and physics; air pollution; interfacial transfer; diffusion and membrane transport.

GEORGE R. GAVALAS, Associate Professor
Ph.D. (1964), University of Minnesota
Applied kinetics and catalysis; process control and optimization.

L. GARY LEAL, Assistant Professor
Ph.D. (1969), Stanford University
Theoretical and experimental fluid mechanics; heat and mass transfer; suspension rheology; mechanics of non-Newtonian fluids.

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

JOHN H. SEINFELD, Associate Professor
Ph.D. (1967), Princeton University
Control and estimation theory; air pollution.

FRED H. SHAIR, Associate Professor
Ph.D. (1963), University of California, Berkeley
Plasma chemistry and physics; tracer studies of various environmental problems.

NICHOLAS W. TSCHOEGL, Professor
Ph.D. (1958), University of New South Wales
Mechanical properties of polymeric materials; theory of viscoelastic behavior; structure-property relations in polymers.

ROBERT W. VAUGHAN, Assistant Professor
Ph.D. (1967), University of Illinois
Solid state chemistry.

W. HENRY WEINBERG, Assistant Professor
Ph.D. (1970), University of California, Berkeley
Surface chemistry and catalysis.
The answer to the above question is YES. Now for the rest of our quiz for the ambitious chemical engineering senior. You'll probably finish in 4 minutes, and it may influence your next 4 years.

Is the Department well rated professionally?
The most recent American Council on Education survey, which samples faculty opinion nationwide, rated us #2 for “strength of graduate program” and #3 on “graduate faculty.” This must mean we try hard, too.

What areas of graduate research are represented?
Which aren’t? With an experienced and distinguished faculty of 20 professors, the Department can offer a tremendous variety of work. For details, please write.*

Let’s try specifics. How about research related to the environment?
At least 7 faculty members have been active in such work. Projects have included: extraction of pollutants from wastewater, electrostatic precipitation of dusts, scrubbing SO2 out of stack gases with seawater, NOx removal from car and plant effluents, design of substitute nonpolluting processes....

The biological sciences seem to be coming to the fore in engineering disciplines. Is this true at Berkeley?
Four ChE faculty members are involved in these interface areas, specifically in biochemical, biomedical, and food processing and production research.

Does this mean that traditional areas are underrepresented?
No way! (See the second question.) Actually, many such areas are represented by more than one professor—electrochemical engineering, fluid mechanics, kinetics and catalysis, mass transfer, materials, process development and design, and thermodynamics.

It sounds like a big operation. Doesn’t this lead to an impersonal quality of education?
We don’t think so. It’s true that the campus is big (27,500 students), although not unusually so these days, and that we have a pretty big graduate group for ChE departments—45 M.S. and 67 Ph.D. candidates. But we have eight graduate advisers, in addition to each student’s thesis adviser, and numerous social and sporting interactions—for example, the summer softball team (can anybody out there pitch?). All together, there is ample opportunity for student-faculty contact.

What is the mean temperature in Berkeley?
Summertime highs average 70°F, wintertime 56°F. Outdoor “summer” sports are year-round activities. Some people get bored with this... but climatic extremes can be reached easily by car.

Can I get to the key libraries and computing facilities conveniently?
Chemistry Library—60 ft., Physics—60 yd., Math—100 yd., Engineering—250 yd., main library—150 yd. (Excuse the English units.) The College has its own computer, and the campus Computer Center—only 100 yd. away—is as close as the terminal in our building.

What opportunities do graduate students have to explore the teaching experience?
Ph.D. students act as teaching assistants for one quarter in each of 3 years during their studies here. M.S. students can occasionally have an opportunity to teach, if they want.

Many urban schools impress the eye as being predominantly concrete. What’s the Berkeley picture?
Two branches of Strawberry Creek run through campus, one within a stone’s throw of the ChE Dept. Numerous redwood trees, tallest grove of eucalyptus in the U.S. The 1300 ft. Berkeley Hills rising steeply behind campus, to the east, San Francisco and 25 miles of Bay Area in view to the west. Parklike landscaping, lots of it—honest. Let’s get back to basics now.

What are the course work requirements for graduate degrees?
For the M.S., 20 graded quarter units, of which 12 must be ChE graduate courses. (Another 10 units must be amassed for the degree, but thesis research and other Pass/Not Pass courses are allowable.) For the Ph.D. no units are officially prescribed, but students are strongly encouraged to explore classes in our department and elsewhere. The catalogue lists 20 ChE regular graduate courses as well as many seminars. The real problem is limiting yourself, in view of the great selection of interesting courses on campus.

How does the Department happen to be in the College of Chemistry?
Simply because we grew out of the Department of Chemistry. Having a two-department College is very cozy, and the strength of the Chemistry Department (e.g., Nobel laureates Calvin, Giauque, Seaborg) is especially helpful for chemical engineers.

How about traditional recreational opportunities in the Bay Area?
You must be joking. We wouldn’t try to capitalize on sailing on the beautiful Bay; skiing and hiking in the majestic Sierra Nevada; the amateur and professional baseball, football, basketball, hockey; the superlative restaurants, museums, and music of San Francisco and the whole Bay Area (Berkeley itself is full of artistic and musical happenings) — would we? Don’t even consider it.

How are thesis research projects assigned to new students?
Students usually select their own projects, from among those offered by the faculty. The only constraint is that Research Assistants must choose from funded projects; fellowship holders are not restricted in this way. Indeed, if you bring your own fellowship, you might even try to design your own project and convince some faculty member to sponsor it.

What is the job market for a Berkeley graduate?
Over the past decade our advanced-degree grads have had exceptional opportunities. Of our Ph.D.’s 1/3 have gone into teaching, 1/3 into chemical and petroleum firms, and 1/3 into other industries. With tightening of the economy, fewer offers are being made everywhere, but industrial prospects are pretty good here. In last year’s grim job market, all our M.S. and Ph.D. grads got good professional jobs, and the general employment situation is improving. Berkeley is visited by more industrial recruiters than any other western school, and the Placement Center is vigorous. The faculty cares, too.

All things considered, would I enjoy and profit from a graduate experience in chemical engineering at Berkeley?
Try it, you’ll like it!
CASE WESTERN RESERVE UNIVERSITY

CASE INSTITUTE OF TECHNOLOGY, a privately endowed institution with a tradition of excellence in Engineering and Applied Science has long offered a variety of courses and research areas leading to the M.S. and Ph.D. degrees in Chemical Engineering. In 1967 Case Institute and Western Reserve University joined together. The enrollment and endowment make Case Western Reserve University one of the largest private schools in the country.

FOR FURTHER INFORMATION YOU ARE INVITED TO WRITE:

Students interested in graduate work in Chemical Engineering or Applied Chemistry should consider the varied opportunities available in the Chemical Engineering Division. Of special interest are strong programs in systems optimization and control, environmental engineering and pollution control, catalysis and surface chemistry, polymer science and engineering, biomedical engineering, materials and reactor design. Within these broad categories are many individual research projects and course offerings.

FINANCIAL ASSISTANCE

Graduate Assistantships are offered with stipends ranging from $450 to $555 per month (depending on background and marital status) from which $200 per month tuition charge is deducted. Appointments are made by either the academic or the calendar year.

Fellowships and Environmental Protection Agency Traineeships are available providing stipends from $200 to $350 per month plus full tuition. Additional allowances for teaching and for dependents are included with some.

Predoctoral loans of substantial amounts are available.

ROBERT J. ADLER, Head
Chemical Engineering Division
School of Engineering
Case Western Reserve University
University Circle
Cleveland, Ohio 44106
COLLEGE OF TECHNOLOGY
DEPARTMENT OF CHEMICAL ENGINEERING
POTSDAM, N. Y.

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CHEMICAL ENGINEERING FACULTY

J. ESTRIN—Prof. and Chmn. (Ph.D., 1960, Columbia University)
Nucleation phenomena in crystallizing systems; condensation of
vapors.

H. L. SHULMAN—Prof and Vice Pres. of the College. (Ph.D., 1950,
University of Pennsylvania) Mass transfer, packed columns;
adsorption of gases; adsorption.

A. F. BURKE—Assoc. Prof. (Ph.D., 1967, Princeton University) High
temperature, electrochemical, and electric arc processes; shock
tube studies; chemical kinetics; combustion; corrosion.

R. COLE—Assoc. Prof. (Ph.D., 1966, Clarkson College of Technology)
Boiling heat transfer; liquid film dynamics.

D. O. COONEY—Assoc. Prof. (Ph.D., 1966, University of Wisconsin)
Multi-component absorption; biomedical engineering; unstable
fluid flow; membrane separation processes; pharmacokinetics.

E. J. DAVIS—Assoc. Prof. (Ph.D., 1960, University of Washington)
Two-phase flow fluid mechanics; convective diffusion; aerosol
physics; mathematical modelling.

J. L. KATZ—Assoc. Prof. (Ph.D., 1963, University of Chicago) Nuclea-
tion phenomena; thermal conductivity of gas mixtures; the equa-
tion of state.

R. J. NUNGE—Assoc. Prof. (Ph.D., 1965, Syracuse University) Dis-
sperion and flow in porous media; pulsating turbulent flow; heat
transfer in multistream systems.

engineering; reverse osmosis; radioactive tracers; nuclear reactor
effluents.

T. J. WARD—Assoc. Prof. (Ph.D., 1959, Rensselaer Polytechnic Insti-
tute) Process systems analysis; multivariable control; analog simu-
lation; properties of materials; thermodynamics.

G. R. YOUNGQUIST—Assoc. Prof. (Ph.D., 1962, University of Illinois)
Kinetics of catalytic reactions; reactor analysis; kinetics and
equilibria of adsorption; crystallization.

S. K. SUNEJA—Asst. Prof. (Ph.D., 1970, Illinois Institute of Tech-
ology) Polymer engineering; air and water pollution; transport
processes.

M. A. BRYNER—Instructor (M.S., 1970, Clarkson College of Tech-
ology) Fluid mechanics;
Three graduate degree programs in several subject areas are offered in the Field of Chemical Engineering at Cornell University. Students may enter a research-oriented course of study leading to the degrees of Doctor of Philosophy or Master of Science, or may study for the professional degree of Master of Engineering (Chemical). Graduate work may be done in the following subject areas.

**Chemical Engineering (general)**
Thermodynamics; applied mathematics; transport phenomena, including fluid mechanics, heat transfer, and diffusional operations.

**Bioengineering**
Separation and purification of biochemicals; fermentation engineering and related subjects in biochemistry and microbiology; mathematical models of processes in pharmacology and environmental toxicology; artificial organs.

**Chemical Microscopy**
Light and electron microscopy as applied in chemistry and chemical engineering.

**Kinetics and Catalysis**
Homogeneous kinetics; catalysis by solids and enzymes; catalyst deactivation; simultaneous mass transfer and reaction; optimization of reactor design.

**Chemical Processes and Process Control**
Advanced plant design; process development; petroleum refining; chemical engineering economics; process control; related courses in statistics and computer methods.

**Materials Engineering**
Polymeric materials and related course work in chemistry, materials, mechanics, metallurgy, and solid-state physics, biomaterials.

**Nuclear Process Engineering**
Nuclear and reactor engineering and selected courses in applied physics and chemistry.

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**Faculty Members and Research Interests**

- Kenneth B. Bischoff, Ph.D. Medical and microbiological bioengineering, chemical reaction engineering.
- George G. Cocks, Ph.D. Light and electron microscopy, properties of materials, solid-state chemistry, crystallography.
- Robert K. Finn, Ph.D. Continuous fermentation, agitation and aeration, processing of biochemicals, electrophoresis, microbial conversion of hydrocarbons.
- Peter Harriott, Ph.D. Kinetics and catalysis, process control, diffusion in membranes and porous solids.
- J. Eldred Hedrick, Ph.D. Economic analyses and forecasts, new ventures development.
- Ferdinand Rodriguez, Ph.D. Polymerization, properties of polymer systems.
- James F. Stevenson, Ph.D. Chemical engineering applications to biomedical problems; rheology.
- Robert L. Von Berg, Sc.D. Liquid-liquid extraction, reaction kinetics, effect of radiation on chemical reactions.
- Herbert F. Wiegandt, Ph.D. Crystallization, petroleum processing, saline-water conversion, direct contact heat transfer.
- Charles C. Winding, Ph.D. Degradation of polymers, polymer compounding, filler-polymer systems, differential thermal analysis.
- Robert York, Sc.D. Molecular sieves, chemical market analyses, chemical economics, process development, design, and evaluation.

**FURTHER INFORMATION:** Write to Prof. Peter Harriott, Olin Hall of Chemical Engineering, Cornell University, Ithaca, New York 14850.
Transport Phenomena & Rheology
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Dr. John C. Biery, Chairman
Department of Chemical Engineering - Room 231
University of Florida
Gainesville, Florida
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The Department of Energy Engineering
UNIVERSITY OF ILLINOIS AT CHICAGO CIRCLE

Graduate Programs in
The Department of Energy Engineering
leading to the degrees of
MASTER OF SCIENCE and
DOCTOR OF PHILOSOPHY

Faculty and Research Activities
in the field of
CHEMICAL ENGINEERING

Lyndon R. Babcock,
Ph.D., University of Washington, 1970,
Associate Professor

David S. Hacker,
Ph.D., Northwestern University, 1954,
Associate Professor

James P. Hartnett,
Ph.D., University of California, Berkeley, 1954,
Professor and Head of the Department

John H. Kiefer,
Ph.D., Cornell, 1961,
Professor

G. Ali Mansoori,
Ph.D., University of Oklahoma, 1969,
Assistant Professor

Irving F. Miller,
Ph.D., University of Michigan, 1960,
Professor

Satish C. Saxena,
Ph.D., Calcutta University, India, 1956,
Professor

Edward J. Schlossmacher,
Ph.D., Princeton University, 1970,
Assistant Professor

Stephen Szepesi,
Ph.D., Illinois Institute of Technology, 1966,
Associate Professor

Air Pollution modeling; environmental problems; polymerization.

High temperature chemical kinetics; combustion and plasma processes; simultaneous transport phenomena.

Forced convection; mass transfer cooling; combined radiation-convection problems.

Kinetics of gas reactions; energy transfer processes.

Thermodynamics and statistical mechanics of fluids, solids and solutions; kinetics of liquid reactions.

Chemical engineering; bioengineering; membrane transport processes; mathematical modeling.

Transport properties of fluids and solids; thermodynamics and statistical mechanics; isotope separation; solid waste management.

Process dynamics and control; process optimization.

Catalysis; chemical reaction engineering; optimization; environmental and pollution problems.

Professor John H. Kiefer, Chairman
The Graduate Committee
Department of Energy Engineering
University of Illinois at Chicago Circle
Box 4348, Chicago, Illinois 60680
IOWA STATE UNIVERSITY

First Land Grant school (1862). Largest College of Engineering west of the Mississippi River and fifth largest in the U.S. Ranks ninth in Ph.D. degrees in Chemical Engineering. Current enrollment of 300 undergraduates and 60 grad students in Chemical Engineering.

PROGRAMS

M.S. and Ph.D. degrees. Five year integrated program for M.E.

FACULTY

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FACILITIES

New, fully equipped Chemical Engineering building with 50,000 square feet of laboratory, office, and classroom space. Adjacent to computer center and to library. Excellent technical support from Engineering Research Institute and technical service groups. Affiliation with the Ames Laboratory, the only National Laboratory of the U.S. AEC located on a university campus.

RESEARCH

International reputation in the following areas:

- Biochemical Engineering (Tsao)
- Biomedical Engineering (Seagrave)
- Coal Research (Wheelock)
- Crystallization (Larson)
- Fluidization (Wheelock)
- Polymer Kinetics (Abraham)
- Process Chemistry (Burnet)
- Simulation (Burkhart)

Outstanding programs also in electronic instrumentation, computer applications to process control, air and water pollution control, extraction, thermodynamics, kinetics and reaction engineering, liquid metals technology, fluid mechanics and rheology, heat and mass transfer, and interfacial and surface phenomena.

FINANCIAL AID

Teaching and research assistantships and industrial fellowships available.

LOCATION

Ames, a small city of 40,000 in central Iowa. Site of the Iowa State Center (pictured above), which hosts the annual Ames International Orchestra Festival and athletic events of the Big Eight Conference.

TO APPLY

Write to:

George Burnet, Head
Chemical Engineering Department
Iowa State University
Ames, Iowa 50010
The Department is the recent recipient of a $150,000 industrial grant for research and teaching in the area of Fluid Flow and Transport Phenomena Applicable to the Petroleum Industry.

Research Areas

Transport Phenomena
Fluid Flow in Porous Media
Process Dynamics and Control
Water Resources and Environmental Studies
Mathematical Modeling of Complex Physical Systems
Reaction Kinetics and Process Design
Nucleate Boiling
High Pressure, Low Temperature Phase Behavior

Financial assistance is available for Research Assistants and Teaching Assistants

For Information and Applications write:

Don W. Green, Chairman
Dept. of Chemical and Petroleum Engineering
University of Kansas
Lawrence, Kansas, 66044
Phone (913) UN4-3922
UNIVERSITY OF KENTUCKY

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Contact: Robert B. Grieves
Dept' of Chemical Engineering
University of Kentucky
Lexington, Kentucky 40506
Chemical Engineering at LSU

... offering master of science, and doctor of philosophy degrees, and a master of science in sugar engineering. Master's candidates may pursue a degree under thesis or course options; the thesis option is encouraged for master's-only candidates.

The department—with new, modern facilities—is equipped with laboratories for research in reacting and thermal fluids, high polymers, and lasers; and with analog, digital, and hybrid computers. The Nuclear Science and Computer Research Centers also service the department. LSU Library holdings near 1,300,000 volumes.

Undergraduate enrollment is 190; and graduate enrollment, 90 (70 master's, and 20 doctoral candidates). Last year, 74 degrees were awarded, including 55 bachelor's, 13 master's, and 6 doctoral degrees.

LSU, a campus of about 19,000 students, is located in Baton Rouge, a major petrochemical center and inland port, capital city, 80 miles north of New Orleans.

For more information, contact:
Dr. Joseph A. Polack, Head
Department of Chemical Engineering
Louisiana State University
Baton Rouge, La. 70803

RESEARCH INTERESTS

Bioengineering
Chemical Kinetics and Reactor Design
Ecology and Pollution Control
Estuarine Studies
Microbiological Laser Irradiation
Physical, Chemical and Thermodynamic Properties of Materials
Polymer Chemistry
Process Control and Dynamics
Pulp and Paper Research
Sugar Technology
Synthetic Foods
Transport Phenomena

THE FACULTY

Philip A. Bryant, Associate Professor, Ph.D.
Clayton D. Callihan, Professor, Ph.D.
Jesse Coates, Alumni Professor, Ph.D.
James B. Cardner, Professor, Ph.D.
Armando B. Corripio, Assistant Professor, Ph.D.
Richard C. Farmer, Associate Professor, Ph.D.
David B. Greenberg, Associate Professor, Ph.D.
Frank R. Groves Jr., Professor, Ph.D.
Douglas P. Harrison, Assistant Professor, Ph.D.
Adrian E. Johnson, Jr., Professor, Ph.D.
Edward McLaughlin, Professor, Ph.D.
Paul W. Murrill, Professor, Provost, and Vice-Chancellor, Ph.D.
Ralph W. Pike, Associate Professor, Ph.D.
Jerome A. Planchard, Jr., Assistant Professor, Ph.D.
Joseph A. Polack, Professor and Head, Sc.D.
Bernard S. Pressburg, Professor and Associate Dean of Engineering, Ph.D.
Roger W. Richardson, Professor and Dean of Engineering, Ph.D.
John J. Seip, Associate Professor and Superintendent of the Audubon Sugar Factory, Ph.D.
Cecil L. Smith, Associate Professor and Chairman, Computer Science Department, Ph.D.
Edgar C. Tacker, Associate Professor, Ph.D.
Alexis Voorhees Jr., Visiting Professor, Honoris Causa.
Albert H. Wehe, Associate Professor, Ph.D.
Bert Wilkins, Associate Professor, Ph.D.
For decades to come, the chemical engineer will play a central role in fields of national concern. In two areas alone, energy and the environment, society and industry will turn to the chemical engineer for technology and management in finding process related solutions to critical problems. M.I.T. has consistently been a leader in chemical engineering education with a strong working relationship with industry for over a half century. For detailed information, contact Professor Raymond F. Baddour, Head of the Department of Chemical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139.

FACULTY

Raymond F. Baddour
Edwin R. Gilliland
Hoyt C. Hottel
Herman P. Meissner
Edward W. Merrill
J. Th. G. Overbeek
Robert C. Reid
Adel F. Sarofim

Charles N. Satterfield
Kenneth A. Smith
J. Edward Vivian
Glenn C. Williams
Lawrence B. Evans
Jack B. Howard
Michael Modell
James H. Porter

Lloyd A. Clomburg
Clark K. Colton
Ian F. Davenport
Richard G. Donnelly
Samuel M. Fleming
Ronald A. Hites
Gary J. Powers
Jefferson W. Tester
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
- Thermionics

**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

FALL 1972
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—Prof. 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
g. Transport Properties and Kinetics—Dr. O. K. Crosser and Dr. B. E. Poling
h. Thermodynamics, Vapor-Liquid Equilibrium—Dr. D. B. Manley

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.
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And Other Areas

WRITE TO
Prof. Lee C. Eagleton, Head
160 Chemical Engineering Building
The Pennsylvania State University
University Park, Pa. 16802
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UNIVERSITY OF PENNSYLVANIA

The University of Pennsylvania is an Ivy League School emphasizing scholarly activity and excellence in graduate education. A unique feature of the University is the breadth of medically related activities including those in engineering. In recent years the University has undergone a great expansion of its facilities, including specialized graduate student housing. The School of Chemical Engineering has also undergone considerable change and growth, attracting national attention because of its rapid rise to excellence.

SCHOOL OF CHEMICAL ENGINEERING

FACULTY
Stuart W. Churchill
William C. Forsman
David J. Graves
A. Norman Hixson
Arthur E. Humphrey
Ronald L. Klaus

RESEARCH SPECIALTIES
Enzyme Engineering
Biomedical Engineering
Computer-Aided Design
Chemical Reactor Analysis
Electrochemical Engineering

For further information on graduate studies in this dynamic setting, write to: Dr. D. D. Perlmutter, School of Chemical Engineering, University of Pennsylvania, Philadelphia, Pennsylvania 19104

Mitchell Litt
Alan Myers
Melvin C. Molstad
Leonard Nanis
Daniel D. Perlmutter
John A. Quinn
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Environmental Control
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Process Simulation
Interfacial Phenomena
Separations Techniques
Graduate Study in Chemical Engineering at Rice University

Graduate study in Chemical Engineering at Rice University is offered to qualified students with backgrounds in the fundamental principles of Chemistry, Mathematics, and Physics. The curriculum is aimed at strengthening the student's understanding of these principles and provides a basis for developing in certain areas the necessary proficiency for conducting independent research. A large number of research programs are pursued in various areas of Chemical Engineering and related fields, such as Biomedical Engineering and Polymer Science. A joint program with the Baylor College of Medicine, leading to M.D.-Ph.D. and M.D.-M.S. degrees is also available.

The Department has approximately 35 graduate students, predominantly Ph.D. candidates. There are also several post-doctoral fellows and research engineers associated with the various laboratories. Permanent faculty numbers 12, all active in undergraduate and graduate teaching, as well as in research. The high faculty-to-student ratio, outstanding laboratory facilities, and stimulating research projects provide a graduate education environment in keeping with Rice's reputation for academic excellence. The Department is one of the top 15 Chemical Engineering Departments in the U.S., ranked by graduate faculty quality and program effectiveness, according to a recent evaluation by the American Council of Education.

MAJOR RESEARCH AREAS
Thermodynamics and Phase Equilibria
Chemical Kinetics and Catalysis
Chromatography
Optimization, Stability, and Process Control
Systems Analysis and Process Dynamics
Rheology and Fluid Mechanics
Polymer Science

BIOMEDICAL ENGINEERING
Blood Flow and Blood Trauma
Blood Pumping Systems
Biomaterials

Rice University
Rice is a privately endowed, nonsectarian, coeducational university. It occupies an architecturally attractive, tree-shaded campus of 300 acres, located in a fine residential area, 3 miles from the center of Houston. There are approximately 2200 undergraduate and 800 graduate students. The school offers the benefits of a complete university with programs in the various fields of science and the humanities, as well as in engineering. It has an excellent library with extensive holdings. The academic year is from September to May. As there are no summer classes, graduate students have nearly four months for research. The school offers excellent recreational and athletic facilities with a completely equipped gymnasium, and the southern climate makes outdoor sports, such as tennis, golf, and sailing year-round activities.

FINANCIAL SUPPORT
Full-time graduate students receive financial support with tuition remission and a tax-free fellowship of $300-350 per month.

APPLICATIONS AND INFORMATION
Address letters of inquiry to:

Houston
Chairman
Department of Chemical Engineering
Rice University
Houston, Texas 77001

Houston
With a population of nearly two million, Houston is the largest metropolitan, financial, and commercial center in the South and Southwest. It has achieved world-wide recognition through its vast and growing petrochemical complex, the pioneering medical and surgical activities at the Texas Medical Center, and the NASA Manned Spacecraft Center.

Houston is a cosmopolitan city with many cultural and recreational attractions. It has a well-known resident symphony orchestra, an opera, and a ballet company, which perform regularly in the newly constructed Jesse H. Jones Hall. Just east of the Rice campus is Hermann Park with its free zoo, golf course, Planetarium, and Museum of Natural Science. The air-conditioned Astrodome is the home of the Houston Astros and Oilers and the site of many other events.

FALL 1972

215
Chemical Engineering

at

Stevens Institute of Technology

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For further information contact:
PROFESSOR JOSEPH BIESENBERGER, HEAD
DEPARTMENT OF CHEMISTRY AND CHEMICAL ENGINEERING
STEVENS INSTITUTE OF TECHNOLOGY
Castle Point Station — Navy Building, Room 315
Hoboken, New Jersey 07030
Programs

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 professional development, or it may serve as preparation for more advanced work leading to the Doctorate. Specialization in Polymer Science and Engineering is available at both levels.

Faculty and Research Interests


Laboratories and Shops

- Computer complex (DEC, PDP 15/35 with interfaces to research labs and analog computer), High-speed automatic frost point hygrometer, Mass and heat transfer in porous media, Polymer rheology and processing (Weissenberg rheogoniometer, Instron rheological tester, roll mill, extruder, Vibron viscoelastometer), Polymer characterization (gel permeation chromatograph, osmometer), Mass spectograph, Continuous zone centrifuge, Process dynamics, X-ray diffraction (including single crystal diffuse scattering analysis), Electron microscopes (Philips EM75 EM300, AMR900), 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 16 full-time technicians and craftsmen.

Financial Assistance

Sources available include graduate assistantships, graduate teaching assistantships, research assistantships, and a variety of fellowships.

Knoxville and Surroundings

With a population near 200,000, Knoxville is the trade and industrial center of East Tennessee. 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, a symphony orchestra, two art galleries, and a number of museums. Within an hour's drive are many TVA lakes and mountain streams for 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.

Students

The Department of Chemical and Metallurgical Engineering has 230 undergraduate and 60 full-time graduate students enrolled at present.

WRITE: Department of Chemical and Metallurgical Engineering, The University of Tennessee, Knoxville, Tennessee 37916
BRIGHAM YOUNG UNIVERSITY
Chemical Engineering Department
M.S. AND Ph.D. PROGRAMS

Areas of Interest
Transport/kinetic processes
Solution thermodynamics
High pressure technology
Environmental Control
Nuclear engineering

Special Research Organizations
Center for Thermochemical Studies
Engineering Fluid Mechanics Research Group
High Pressure Laboratory
Center for Environmental Studies

Faculty
Dee H. Barker
James J. Christensen
Dwight P. Clark
Ralph L. Coates
Joseph M. Glassett
H. Tracy Hall
Richard W. Hanks
M. Duane Horton
Bill J. Pope
Vern C. Rogers
L. Douglas Smoot, Chairman
Grant M. Wilson

FOR INFORMATION CONTACT
Dr. Richard W. Hanks
Graduate Coordinator
234 FELB, Chemical Engineering
Brigham Young University
Provo, Utah 84601

DEPARTMENT OF CHEMICAL ENGINEERING
BUCKNELL UNIVERSITY
LEWISBURG, PENNSYLVANIA 17837

For admission, address
Dr. Paul H. DeHoff
Coordinator of Graduate Studies

• 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, solid-liquid, and liquid-liquid extraction; thermodynamics; mathematical application in chemical systems; reaction kinetics; process dynamics and control; metallurgy and the science of materials; biomedical engineering.
• Assistantships and scholarships are available.
• For the usual candidate, with a B.S. in Chemical Engineering, the equivalent of thirty semester-hours of graduate credit including a thesis is the requirement for graduation.
UNIVERSITY OF CALIFORNIA, DAVIS

CHEMICAL ENGINEERING, M.S. AND PH.D. PROGRAMS

Faculty

R. L. Bell: Mass Transfer, Bio-Medicine
N. A. Dougharty: Catalysis, Chemical Kinetics
A. P. Jackman: Process Dynamics, Thermal Pollution
B. J. McCoy: Molecular Theory, Transport Processes
J. M. Smith: Water Pollution, Reactor Design
S. Whitaker: Fluid Mechanics, Interfacial Phenomena

Write To:

Graduate Student Advisor
Department of Chemical Engineering
University of California
Davis, California 95616

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Graduate education is not for everyone. We believe, however, that it is the best means for an engineer to develop his potential and at the same time become better equipped to influence society in a positive way.

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Paul G. Mikolaj
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G. Robert Odette
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For information, please write to: Department of Chemical and Nuclear Engineering
University of California, Santa Barbara 93106

FALL 1972
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FOR FURTHER INFORMATION, PLEASE CONTACT:

Department of Chemical Engineering
The Cleveland State University
Euclid Avenue at East 24th Street
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Telephone: (216) 687-2569
Graduate Study in Chemical Engineering
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FOR MORE INFORMATION WRITE TO
Professor B. G. Kyle
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FALL 1972
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M. CHARLES
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GRADUATE STUDY IN CHEMICAL ENGINEERING
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CURRENT RESEARCH AREAS:
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- Polymer Engineering
- Biomedical Engineering
- Air and Water Pollution
- Thermodynamics
- Particulate Dynamics
- Catalysis
- Solid-Liquid Separation
- Cryogenics
- Chemical Reactors
- Plasma Research
- Fluidisation
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A. Benedek (Ph.D., U. of Washington) . . . . Wastewater Treatment, Novel Separation Techniques
C. M. Crowe (Ph.D., Cambridge) . . . . Optimization, Chemical Reaction Engr., Simulation
I. Feuerstein (Ph.D., Massachusetts) . . . . Blood Flow, Transport Phenomena
A. E. Hamielec (Ph.D., Toronto) . . . . Polymer Reactor Engr., Transport Phenomena
J. W. Hodgins (Ph.D., Toronto) . . . . Polymerization, Applied Chemistry
T. W. Hoffman (Ph.D., McGill) . . . . Heat Transfer, Chemical Reaction Engr., Simulation
J. F. MacGregor (Ph.D., Wisconsin) . . . . Statistical Methods in Process Analysis
K. L. Murphy (Ph.D., Wisconsin) . . . . Wastewater Treatment, Physicochemical Separations
J. D. Norman (Ph.D., Rice) . . . . Wastewater Treatment, Biochemical Reactions
L. W. Shemilt (Ph.D., Toronto) . . . . Mass Transfer, Corrosion
J. Vlachopoulos (D.Sc., Washington U.) . . . . Polymer Rheology, Heat Transfer
D. R. Woods (Ph.D., Wisconsin) . . . . Interfacial Phenomena, Particulate Systems
J. D. Wright (Ph.D., Cambridge) . . . . Process Simulation and Control, Computer Control

DETAILS OF FINANCIAL ASSISTANCE AND ANNUAL RESEARCH REPORT AVAILABLE UPON REQUEST

CONTACT: Dr. C. M. Crowe, Chairman
Department of Chemical Engineering
Hamilton, Ontario, Canada

THE UNIVERSITY OF MICHIGAN
CHEMICAL ENGINEERING GRADUATE PROGRAMS
on the ANN ARBOR CAMPUS

The University of Michigan awarded its first Chemical Engineering M.S. in 1912 and Ph.D. in 1914. It has moved with the times since and today offers a flexible program of graduate study that allows emphases ranging from fundamentals to design.

The Chemical Engineering Department, with 21 faculty members and some 70 graduate students, has opportunities for study and research in areas as diverse as: thermodynamics, reactor design, transport processes, mathematical and numerical methods, optimization, materials, mixing, bioengineering, electrochemical engineering, rheology and pollution control.

The M.S. program may be completed in 10 months and does not require a thesis. The Professional Degree requires thirty-hours beyond the Master's and a professional problem. The Ph.D. program has recently been revamped to expedite entry into a research area as early in the program as possible.

For further Information and applications, write:
Chairman of the Graduate Committee
The University of Michigan
Department of Chemical Engineering
Ann Arbor, Michigan 48104
Applications are invited for Monash University Research Scholarships tenable in the Department of Chemical Engineering. The awards are intended to enable scholars to carry out under supervision, a programme of full-time advanced studies and research which may lead to the degrees of Master of Engineering Science and/or Doctor of Philosophy.

Facilities are available for work in the general fields of:

- Solid-gas Thermodynamics and Kinetics
- Packed Tubular Reactors
- Crystal Nucleation and Growth
- Fluidisation
- Rheology
- Computer Control and Optimisation
- Gas Absorption with Reaction
- Waste Treatment Engineering
- Process Dynamics
- Biochemical Engineering
- Fluid - Particle Mechanics
- Mixing of Liquids
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