



chemical engineering education

CHEMICAL ENGINEERING DIVISION OF AMERICAN SOCIETY FOR ENGINEERING EDUCATION

SUMMER 1969

CHE EDUCATOR

Dean

Max Peters

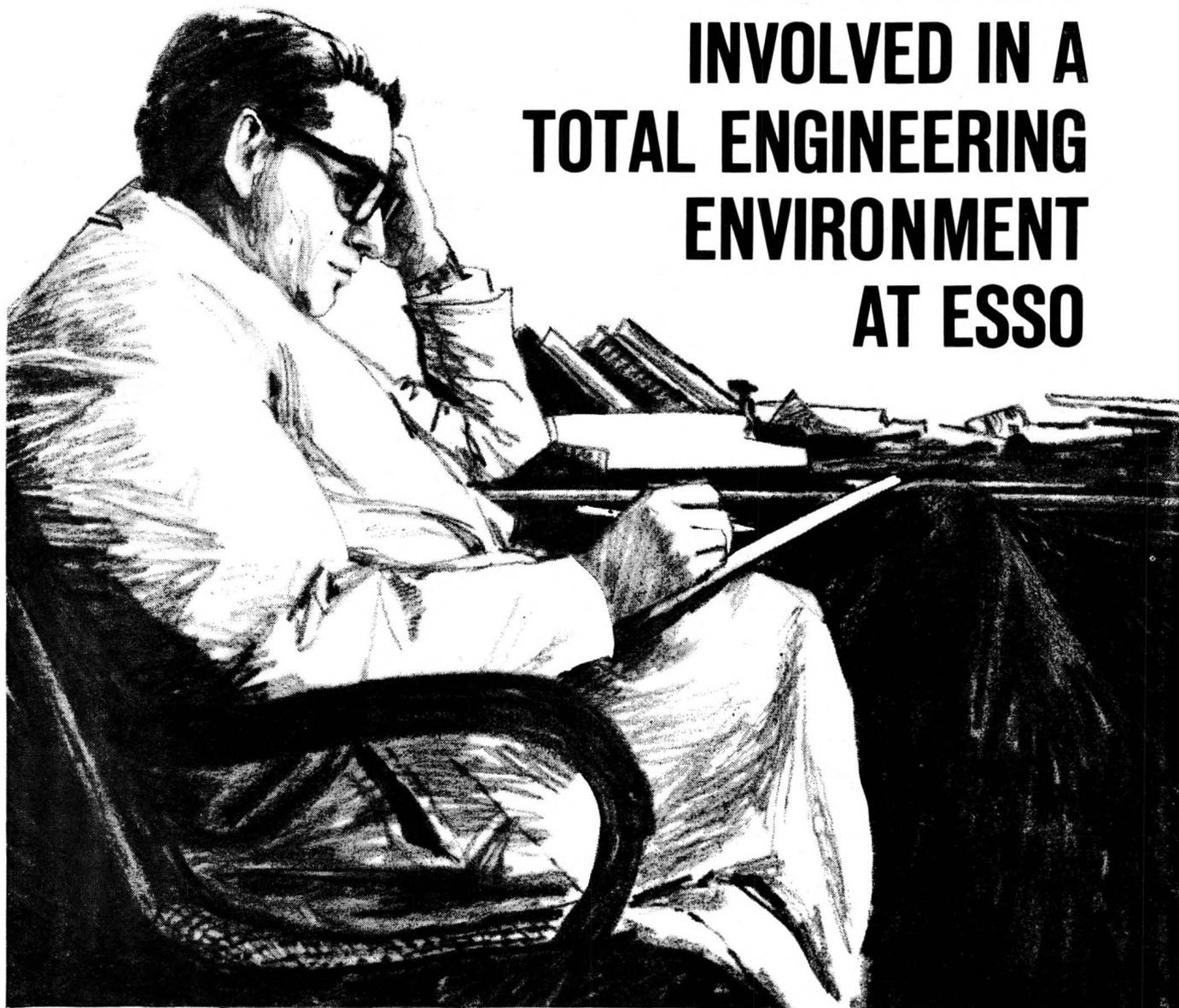
of Colorado



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CHEMICAL ENGINEERING EDUCATION is published quarterly by the Chemical Engineering Division, American Society for Engineering Education. The publication is edited at the Chemical Engineering Department, University of Florida. Second-class postage is paid at Gainesville, Florida, and at DeLand, Florida. Correspondence regarding editorial matter, circulation and changes of address should be addressed to the Editor at Gainesville, Florida 32601. Advertising rates and information are available from the advertising representatives. Plates and other advertising material may be sent directly to the printer: E. O. Painter Printing Co., 137 E. Wisconsin Ave., DeLand, Florida 32720. Subscription rate U.S., Canada, and Mexico is \$10 per year to non-members of the ChE division of ASEE and \$6 per year to members. Individual copies of Vol. 2 and 3 are \$3 each.



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REPORT to our Readers

Chemical Engineering Education has now published six issues and completed one and a half years of publication at the University of Florida. It is both surprising and gratifying to the editors that the publication continues to be well-received by the profession. Although we have expected our luck to run out, each issue seems to bring forth new commendatory letters and comments and there seems to be general agreement that the publication is filling an important need. We very much appreciate these expressions of support, but we realize that we are still amateurs in the publishing business. We cannot compete with commercial ventures or professional journals that are published by large societies and supported by dues.

During the past year we have again had an excellent response from our colleagues who have submitted manuscripts for publication. We have not been able to accept all papers submitted to us (rejected papers have usually been negatively reviewed, but a few have been deemed inappropriate for our journal.) Our editorial policy in each issue has been either to emphasize some particular theme or to try to achieve a balance among articles. The latter means not only that we try to have an article for every recurring department (e.g. Chemical Engineering Classroom), but also that we try to have represented in the issue the various technical areas of the profession. We also try to achieve balance among articles published in terms of type of school (public, private, graduate-oriented, undergraduate-oriented, etc.) and geographical location. While we have appreciated the opportunity to publish papers from some well-known people in the profession, we do not in any way discriminate against lesser-known but capable people from the undergraduate-oriented schools. We feel our journal is for the profession as a whole and not just an elite group or "in-group" of any kind.

The above policies also apply to the selection of our featured departments and featured educators. Here we have generally had an excellent response from people whom we have asked to write articles. However, there were two schools who were unable to submit a department article for this issue. As a result we have been forced to get together a last minute article on our own department—even though we have assiduously tried to avoid using articles from our own de-

partment in the journal. (Apparently we have been reasonably successful in not playing up our department, since a good number of visitors have commented on the journal without knowing we were publishing it!)

In order to survive it is necessary that we receive the financial support of departments, advertisers, and industrial donors. We have appreciated the fact that, due to the efforts of Joe Bergantz, nearly 100 departments are now contributing to **CEE**! However, last fall, the prospects for advertisements and donations seemed so gloomy, that we reduced our number of pages by eight. Since then, I am happy to report, the yeoman efforts of Professor Weber and the Publication Board have been paying off. It now looks like our combined industrial advertising and donation income will be within a few hundred dollars of last year's figure and could even be more than last year! Even brighter, however, are the prospects for the success of George Burnet's suggestion that the fall issue go to seniors interested in graduate work and that we seek departmental ads on graduate programs for the fall issue. Professor Bergantz states that now about 30 departments have indicated that they intend to buy a total of \$3000 of such advertising of which the increased costs of printing additional pages and 2000 more copies will be about half that amount.

Incidentally, since the Fall issue of **CEE** will carry paid advertisements from ChE departments and will go to seniors interested in graduate work, we felt the editorial content should emphasize basic areas of instruction and research in graduate studies. Accordingly prominent chemical engineering scholars will write on their graduate courses in certain important areas (such as control and optimization, thermodynamics, kinetics, applied mathematics, particular systems, etc.). Each article will outline a graduate course and indicate important areas of research in the field. In this manner we hope to encourage more seniors to continue their intellectual growth in graduate school.

R.W.F.

P.S. The Publications Board recently approved, effective January 1970, a charge to ChE Division members of \$6/yr. each for subscriptions. Bulk subscriptions to departments will be \$4/yr. each with a minimum charge of \$25. We expect to reach more faculty members this way and also to generate additional income.

NOTES TO AUTHORS:

P.S. We have a few words of instruction for future authors. Because of the limited amount of space available, the articles, papers or reports submitted to CEE should be concise, lucid and also brief. Follow nomenclature of standard textbooks or write equations or formulas clearly. Use consistent units of measurement and give dimensions for all terms.

Assume your reader has some expertise in the field and minimize the amount of historical background included. Avoid tables and graphs which involve duplication or unnecessary data. Frequently a graph or a few typical results may be substituted for a lengthy table.

Two copies of a paper are sufficient for review. After a paper has been accepted for publication, the author should send the editor a short biography and photo of himself to use with the article. M.T.

ACKNOWLEDGMENTS

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from the READERS

Correction from Lih

Sir: The beginning of the article on Stu Churchill (CEE Spring 1969) clearly illustrates what the chemical engineering teacher has to do these days. You have to stand on your head to catch the attention of students. Perhaps this is why Professor Churchill has been so successful and has had to engage in all sorts of athletic activities to keep it up.

The Japanese (and Chinese as well) character for HYO (leopard) is upside down.

Marshall M. Lih
Catholic University

Statistical Study

Sir: We have made a study which attempts to relate mathematically the number of staff members of professional rank required in a chemical engineering depart-

ment to the numbers of bachelors, masters and doctors graduated per year. No similar study could be found in the literature.

One purpose of this study was to analyze the relationship between the number of persons of professorial rank required in a chemical engineering program and the number of students to be graduated per year at various degree levels. In light of the rapid expansion currently taking place in most universities it is important that this relationship be understood in order that intelligent administrative and educational decisions and forecasts may be attempted. In the present study this relationship is analyzed only for chemical engineering programs since this case was of immediate concern to the authors. The main problem involves estimating how much of the total variability in the number of professors of chemical engineering from university to university is due to the different numbers of degrees granted, and how much is due to "other factors" such as

Different emphasis on research activities
Different policies concerning the amount of administrative work to be performed by the professors

Different professor-student ratios
Different student attrition or "drop-out" rates
Different amounts of teaching done by non-professional staff members
Different numbers of students per class

Henceforth, these "other factors" will be referred to as educational, administrative and research policies.

If it is assumed that the departments of chemical engineering in our American colleges and universities have the same educational, administrative and research policies, the following equation will hold.

$$P = A_0 + A_1B + A_2M + A_3D \quad (1)$$

where P is the number of full-time teaching schedules required in the professorial ranks (total of Assistant, Associate and Full), B, M, and D are, respectively, the number of bachelor's, master's and doctoral degrees granted per year, and A_1 , A_2 and A_3 represent respectively the additional numbers of professors needed for each additional bachelor's master's or doctoral degree granted per year.

However, as would be expected, deviations from Eq. 1 are observed, presumably because universities do not have the same educational, administrative and research policies and are at considerably different stages of development. In order to estimate the proportion of the total variation due to the different numbers of degrees granted and how much is due to the difference in educational, administrative and research policies, the technique of least squares was used.

Data from accredited chemical engineering departments of 97 universities for the academic year 1964-1965 were gathered from *Chemical Engineering Faculties of Canada and the United States*, which is compiled annually by the Chemical Engineering Projects Committee of AIChE. For each of the 97 universities, the number of professorial schedules in chemical engineering was obtained along with the number of bachelor's, master's and doctor's degrees granted. By calculations performed on an IBM 7040 digital computer, the least squares estimates of A_0 , A_1 , A_2 , and A_3 were found to be 3.40, 0.06, 0.15 and 0.43 respectively, yielding the equation

$$P = 3.40 + 0.06B + 0.15M + 0.43D \quad (2)$$

Thus we can estimate that for every additional professor employed, schools can grant, on the average, an additional 16-2/3 bachelor's degrees, or 6-2/3 masters degrees or 2-1/3 doctors degrees per year and conversely. It should be emphasized that these figures are estimates of average behavior and that the situation in any one school may depart markedly from these estimated averages.

The multiple correlation coefficient was found to be 0.79. Accordingly, one may estimate that 0.62 (which is 0.79^2) of the total variation in the number of professorial schedules in chemical engineering from university to university may be explained by the different numbers of degrees granted while the residual 0.38 (which is $1.00 - 0.62$) of the variation may be attributed to the different educational, administrative and research policies prevailing.

A second objective of the present study was to determine changes with time in the coefficients such as those calculated and presented in Eq. 2 in the light of the very rapid educational growth rates and rapid changes in student degree objectives currently occurring on the

American educational scene.

Data for 70 departments of chemical engineering for the year 1962-63 had been analyzed and reported in a previous study.*

The least squares equation for these data had been found to be

$$P = 2.2 + 0.10B + 0.1M + 0.45D \quad (3)$$

It is interesting to speculate on the results of the two studies. A multiple correlation coefficient of 0.83 obtained from the 1962-63 data against the value of 0.79 in the current study indicates a reasonable degree of year-to-year stability despite the relatively rapid changes currently occurring in Academia. The large change from 2.2 to 3.4 in the constant terms of Eqs. 3 and 2, may indicate that in the 1964-65 period, considerably more professorial time was allotted to administrative and other non-teaching activities than in the 1962-63 period. We come next to the coefficients of B. If we assume a Gaussian distribution, the difference between the coefficients of B in equations 2 and 3 does not (at the 10% level) turn out to be statistically significant. However, since there is no *a priori* basis for assuming a Gaussian distribution, the observed difference may be significant. It is interesting to note that if the difference is significant in fact, then it is in the expected direction; i.e., downward, indicating that fewer professors were required per bachelor degree granted during the 1964-65 period than were required during the 1962-63 period. The trend towards larger lecture sections requiring fewer professors per student as well as an increase in instruction by graduate assistants has certainly been observed during recent years. Finally, with regard to the coefficients of the M and D terms in Eqs. 2 and 3 one can only say that the agreement is indeed striking and beyond what one might expect. To determine to what degree the above conjectures are correct would of course require direct corroboration in depth from the institutions involved. At any rate, the implied stability of the results of these studies is gratifying. It indicates that similar analyses in the future may be desirable and useful.

Because of radical differences in the procedures, policies and manpower requirements of graduate and undergraduate programs, it was decided, as a third objective of this study, to try to analyze separately a group of schools heavily oriented toward graduate work as distinct from a group that is not. To distinguish between them the following purely arbitrary criteria were set up. For each institution the ratio of the combined number of master's and doctoral degrees (in ChE) to the number of undergraduate degrees was determined. If the ratio was greater than 0.4, or if there were five or more doctoral degrees granted in ChE for the year the school was considered to be graduate-inclined. On this basis the 97 schools subdivided into 40 graduate-inclined and 57 undergraduate-oriented schools.

In both groups, a least squares analysis was performed as in the case for all 97 schools with the following results:

*Schmidt, A. X. and Pfeffer, R., CEE, p. 13 (October 1965).

(Continued on page 143.)

MAX PETERS

University of Colorado

If there is a better way of educating engineers, Max S. Peters, dean of the College of Engineering at the University of Colorado, will be in pursuit of it. "Finding a better way" could be the most fitting description characterizing his performance, whether inside or outside the classroom, the administrative halls of higher education, the laboratory, or the smoke-filled committee rooms in which he is such a driving force.

Something of the vigor and hardihood of the Ohio-Pennsylvania early American certainly is evident in Max Peters. He was born in 1920 in Delaware, Ohio, and received his early education in State College, Pennsylvania, and at Penn State University. He earned the PhD degree in chemical engineering at Penn State in 1951, performing research on vacuum distillation.

By the time he was awarded his degree he had already worked as a production supervisor in a wartime powder plant and had served with distinction in the 10th Mountain Division of Italy. For two postwar years he was in charge of all technical work for Treyz Chemicals in Cook Falls, New York.

Colleagues and students alike are apt to address him as Max. They appreciate his capacity for hard work and the sense of humor that is ready to break to the surface in the midst of serious considerations. *His door is always open to his graduate students. As one of them puts it, "I'm amazed that a man with so many responsibilities can be so available."*

The responsibilities he has are the result of his diligent research for "a better way." He heads a college enrolling nearly 2000 undergraduate and some 300 graduate students, with a faculty numbering around 125, housed in a new \$8.5 million educational facility which he himself worked hard to make a reality. In addition, he guides engineering programs at two off-campus CU Centers, at Denver and Colorado Springs.

The story of the remarkable growth of the College of Engineering at the University of Colo-



Max Peters, newly appointed in 1962 as dean of the College of Engineering at the University of Colorado, enthusiastically pushed forward plans for the proposed Engineering Center, dedicated in May, 1966.

rado since Max Peters arrived on campus in July of 1962 is well known to engineering educators across the country. He hadn't been in office long before the building priority for the proposed Engineering Center moved up from eleventh to first. Then he went to work with the University administration to acquire \$7.2 million from the state legislature for construction of the Engineering Center — the largest sum ever requested from the people of Colorado. He further exerted his persuasive and organizing powers to acquire a supplementary \$1.325 million from the National Science Foundation.

The Engineering Center at CU can truthfully be said to have been inspired in great part by the enthusiasm and imagination of Max Peters. At ground-breaking ceremonies for the Center in 1964 he revealed the scope of his expectations when he described the Center as "a major milestone . . . in the forward progress of making the State a major industrial and scientific center."

He tackles the challenge at its grassroots — the high school level — with the same bold enthusiasm. "Is there anything wrong," he asks, "with being old fashioned and strongly encouraging our high school students to start preparing themselves while in high school?"

"To be what you can be, you must first and foremost decide what you want to be."

Many of his colleagues and students have heard him say, "Engineering is a tremendously exciting and rewarding career!" and in a diversity of situations he proclaims vehemently, "It is time that some of us decide to speak out."

Max showed signs of "speaking out" in his first academic position, as assistant professor, then professor, and then divisional head of chemical engineering at the University of Illinois. There he began the characteristic pattern: to examine and re-examine the curriculum to expose its weaknesses, identify its strength, and take action to improve it. At Illinois he recognized the need for more extensive chemical engineering kinetics study and introduced a course to fill the void.

His first book, *Elementary Chemical Engineering*, (McGraw Hill, 1954) was written at Illinois to fill a gap in engineering education for students of other disciplines such as mechanical engineering and chemistry. The text has been especially valuable in foreign countries where teachers were not capable of using standard texts for chemical engineer majors.

In his second book, *Plant Design and Economics for Chemical Engineers*, (McGraw Hill, 1957) Max Peters tackled another need — that of graduate students who went into design work in the chemical industry with relatively little background in plant design problems and their solutions. *Plant Design* has been adopted by more than half of the chemical engineering curricula across the country. A completely revised edition (1968), written with Klaus D. Timmerhaus, associate dean of the CU College of Engineering, provides greater depth in optimization and economic evaluation.

Both books are considered classics in that they speak to engineers of all disciplines and to scientists and industrial managers who have no formal educational background in chemical engineering.

It was at Illinois that Dean Peters' drive to improve educational standards carried him into the local chapter of the AIChE as faculty representative. Years of committee activity brought him in 1968 to the presidency, where he committed himself wholeheartedly to the quest for improved engineering education and true professionalism by AIChE members, and to the pro-



When Max Peters takes part in Fun & Games at the E-Days picnic only his plaid shirt distinguishes him from the students.

profession's obligation to assist society in the solution of its problems. His improvements in the professional society, (among them he originated the popular Free Forums) are well known to AIChE members. Through the voice of AIChE Max has supported the concept of the chemical engineering degree instead of the general engineering degree as the first professional degree.

As head of the chemical engineering division at Illinois, Max Peters recognized that chemical engineering students engage in a wide scope of activities including economics, technical services, laboratory research. Accordingly, he introduced a flexibility into the undergraduate curriculum that allowed the student to substitute advanced mathematics, physics, and chemistry for more conventional courses. His incorporation of fundamental engineering sciences into the undergraduate program has been copied by chemical engineering departments in many institutions throughout the United States.

It was natural for Max to strive toward raising the standards of excellence in the College of Engineering at the University of Colorado. With Dean W. L. Everitt of Illinois he initiated the Bi-University Institutional Liaison for Development (BUILD) program for experimentation and development of faculty innovative ideas between the two universities. Now concluding its fourth year of support by the Kettering Foundation, BUILD has implemented exchanges for professional development that have involved at one time or another every faculty member of the CU College of Engineering.

Max is a forceful and articulate committee member, as many of his colleagues have learned. As chairman of the CU proposal committee for the National Science Foundation Scientific Development program, he helped bring \$3.75 million

to the University of Colorado, one million of which went into electrical, aerospace, and mechanical engineering programs in the College of Engineering. As a result, the College has strengthened its programs in control theory, solid state physics, computer logic, fluid mechanics, applied mechanics and mathematics. Growth in these areas is being watched with interest by other institutions.

Behind this vigorous activity Max holds a philosophy that has deeply affected graduate study and research throughout the College. Graduate students, he holds, should be actively involved in research programs under the direction of faculty members. Faculty members who are engaged to fill needs in research areas must be good teachers. Funding for this program has increased during the past five years from less than \$200,000 to approximately two million dollars.

In 1961, one PhD degree was awarded by the University of Colorado to a student in engineering. In 1968, 30 engineering students earned the degree. PhD degrees have been made available in aerospace engineering sciences and in mechan-

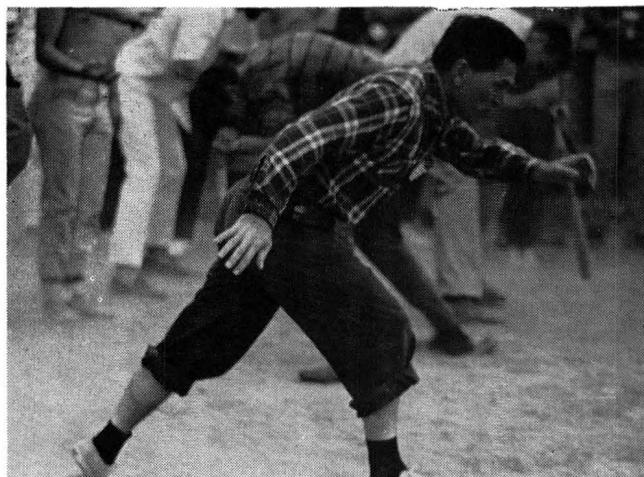
"Is there anything wrong," he asks, "with being old fashioned and strongly encouraging our high school students to start preparing themselves while in high school?"

ics in addition to all the other departments, with the exception of a new department, Engineering Design and Economic Evaluation, which offers the master's degree.

It's easy for graduate students to discuss their research problems with Max Peters; in fact, he is himself making a significant contribution in the laboratory. His research studies in kinetics, particularly on nitrogen oxides and pentaerythritol, have resulted in increased understanding of reaction mechanisms and in the chemical engineer's ability to design reactors. He personally directs graduate work in allied studies.

He gives his students as much freedom as possible in their projects, only outlining the overall view and the goal. He believes that students learn more from doing a thing wrong than from doing it right the first time. This freedom to experiment encourages his students to be creative and analytical.

They recognize his qualities as a teacher. "He took the complex and broke it down into simple integral parts," one of his students comments,



As usual, Max Peters won the Dean's Challenge Race at the E-Days picnic in May, 1968.

or, "He built up the complicated theories of chemical engineering by starting with easily understood building blocks of knowledge."

As a teacher, characteristically Max looks for better ways to explain points and ideas; he designs quizzes and exams to test a student's comprehension rather than his memory of equations and data. The secret of his ability is simple: he is truly interested in each of his students as a person. Because of this, he is able to instill in his students the desire to be successful in study and experimental work. Typically, his plant design students have repeatedly won or placed near the top in the national AIChE Student Contest Problems.

Students have discovered their Dean is a formidable contestant on the ski slopes and the Engineers' Days races. They hail him as champion of faculty-student slalom race at the CU Winter Carnival, and know him as an accomplished figure-skater. Every year Dean Peters has won the Dean's Challenge Race at the E-Days picnic.

He wears his more impressive honors with modesty. This spring he was elected a member of the National Academy of Engineering — the highest professional distinction that can be conferred upon an American engineer. He is cited this June by the American Association of Cost Engineers for his "continuing contributions to the field of cost engineering education." He was recently named chairman of the President's Committee on the National Medal of Science.

In 1957 Max Peters received the George Westinghouse Award from the American Society for Engineering Education for outstanding teaching. He has been active in the ASEE for nearly ten years. In 1962 he served as chairman of the

The secret of his ability is simple—he is truly interested in each of his students as a person.

Chemical Engineering Division and was for six years a member of the long range planning committee of ASEE.

He is active on the air pollution committee of the U. S. Department of Health, Education, and Welfare, which he serves as consultant. He is consulting editor for the McGraw Hill Chemical Engineering Series, and is the author of many technical articles.

Anyone who knows Max knows him as the embodiment of a belief he has expressed to high school students and to AIChE members: "To be what you can be you must first and foremost decide what you want to be." Since he will never be satisfied with things as they are, but must always seek new and better answers, it follows that Max Peters is not only dean, teacher, chemical engineer, researcher, and innovator. He is perhaps first of all a student — a student of education.

OPTIMIZATION

APPLICATIONS AND LIMITATIONS**

RICHARD R. HUGHES*
Shell Development Company
Emeryville, California

THE OPTIMIZATION MODEL

To begin with, optimization requires a formal description of the problem. The elements involved and their relationship are indicated in Fig. 1. First, the problem must be isolated by a formal description of the "state-of-nature" and the problem premises. This is often the most difficult part of the problem. A sound treatment requires an assessment of whether the solution will answer the question posed and whether all significant variable elements are included within

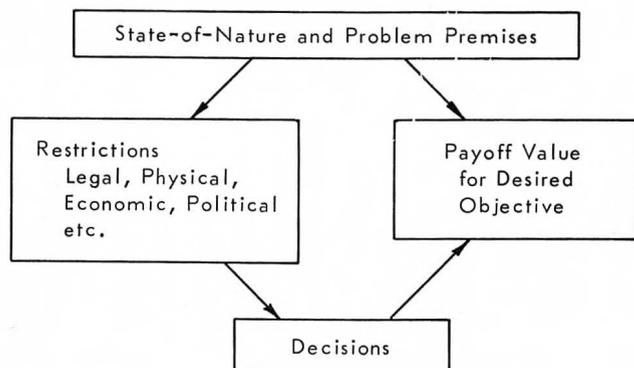


Figure 1.

Optimization implies logical, even formal, decision making, i.e., the selection, for a set of *decision variables*, of the best attainable (and allowable) values for a designated *objective*. To successfully accomplish optimization of practical non-trivial problems, two major requirements must be met. First, we must have access to computers (normally large digital computers), and we must be able to use them. This, of course, implies optimization of a mathematical model describing the problem; the second requirement is that this model must be the simplest possible one for the job at hand. The calculation will be extremely repetitive; and any but the simplest possible model will require excessive computation and make it uneconomic to use optimization.

In this paper, I first describe my concept of an optimization model. Then I propose guidelines for formulation and simplification of such models. Finally I offer a few remarks on limitations and complications of the optimization approach. My comments are based on several years of study and practical application of optimization, —by myself and many colleagues,—to problems in chemical engineering, process design, and operations research. Most of the rules given are not hard and fast limitations but merely express my observations of difficulties we have encountered.

the system. Obtaining an optimum scale of manufacture at a fixed sale price is absurd if the scale affects the sales price. With the state of nature established we then identify the decisions we are still free to make. As functions of these decisions, we describe the payoff value, and formulate the necessary restrictions which dictate limitations on the problem, — legal, physical, economical, political, etc. These restrictions limit the freedom of action of our decisions, but there is usually some variability left. By optimizing, we take ad-

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** Presented at the Los Angeles ASEE meeting June 19-22, 1968.

vantage of this variability to obtain the best possible payoff value.

When formulated as a mathematical model, the problem has the form indicated in Fig. 2. The state of nature and problem premises are

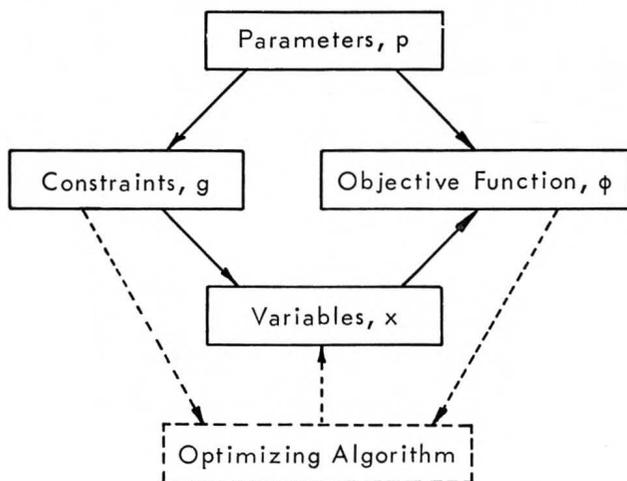


Figure 2.

described by a vector of parameters, p , which includes prices, sales figures, coefficients of correlations, estimated technical values, and all the many other numbers which must be used to quantify the problem. The payoff value is formulated as an object function, ϕ , whose value is determined by the decision variable vector, x , and the parameter vector, p . The various limitations are described as a vector of constraint functions, g , each element of which must be non-negative for an allowable or *feasible* solution. Once the problem is described in this format, we can optimize it by using an optimizing algorithm to adjust the variables, x , to obtain the best value of ϕ within the limitations of the constraints. Mathematically, this can be written as follows:

$$\text{Max}_x \left\{ \phi(p, x) \mid g(p, x) \geq 0 \right\} \equiv \phi^*(p) = \phi(p, x^*) \quad (1)$$

The first part of this equation is read: "find the maximum over the variable space x of the function ϕ of p and x subject to the non-negativity of the elements of the vector g , which are functions of p and x ." The resulting maximum or "optimum," ϕ^* , is a function of the parameter vector p , which describes the particular case which has been optimized. Corresponding to ϕ^* there are one or more points, x^* , in variable space x , where $\phi = \phi^*$. These values are usually the most important part of the result; they indicate the optimum or best choice of variables. Impliedly,

it is clear that the optimum choice, x^* , is a function of the parameter vector p .

OPTIMIZATION ALGORITHMS

For further information as to the details of the optimization algorithms, ample literature exists. For elementary introduction, there is a good book by Baumol on *Economic Theory and Operations Analysis*³ and a somewhat more mathematical treatment by Carr and Howe⁵. In the limited but important field of linear programming, Dantzig's book⁶ is the fundamental authority; it is sound and intelligible, but a little long. The book by Gass¹⁰ on the other hand is quite elementary; for an intermediate level, that of Hadley¹³ is probably best. Hadley's second book¹⁴ extends the treatment to non-linear programming, with emphasis on systems of many dimensions. For those interested in these more-mathematically oriented problems, the collection edited by Graves and Wolfe¹¹ is a good review of the state of the art in 1963. However, for many chemical engineering problems, Wilde's recent book on "Optimum Seeking Methods"³¹ is more directly applicable. Two recent collections also supply useful hints on this latter type of problem: the CEP Symposium Series volume on "Optimization Techniques",⁴ and the book edited by Lavi and Vogl.¹⁹ A last general reference, we cite the recent review by Wilde,³² which includes 74 references of recent work.

In much of our work, we have used optimum-seeking methods as described in the later references listed above. Our particular versions are described briefly by Singer²⁹; one of them (the Maze Method) is described in more detail by Mugele.²² We have also found the MAP method of Griffith and Stewart¹² to be generally applicable and quite powerful. Finally, for the problems to which they apply, Rosen's methods, Gradient Projection²⁵ and Partition Programming^{26, 27}, have been quite successful. With these and many more methods available, further extensive work on mathematical programming or optimization algorithms does not seem worthwhile for the engineer. However, the method chosen must be a suitable one for the problem at hand and the computing equipment available; with large problems, the performance of the algorithms depends strongly on the particular configuration of the computer.

OPTIMIZATION PROBLEMS

Most optimization problems of interest to a chemical engineer can be fit into one of four categories: (1) process design, (2) operations scheduling, (3) process control, and (4) equipment design.

1. Process Design

In many respects, this is the most important category. Problems of this type range from detailed process design (to choose the best possible configuration of many process details) to quick and rather generally formulated process evaluation (to provide a general pattern of possible profitabilities of a proposed new process or product). To illustrate the features of process design optimization, we use the example shown in Fig. 3. Although this example was developed independently, it is quite similar to the one presented by Williams and Otto³³ and studied by DiBella and Stevens.⁷

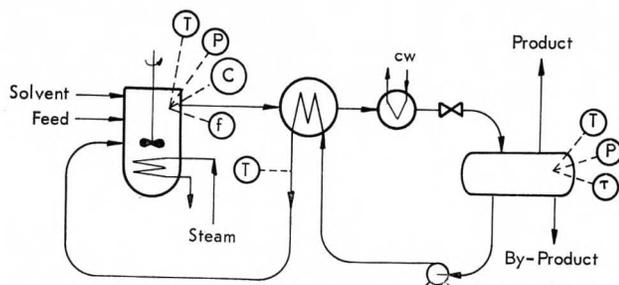


Figure 3.

Our example considers the reaction of a pure hydrocarbon with a solvent to produce a desired volatile product. The product reacts with excess solvent to produce an insoluble and undesirable sludge. For simplicity, we use a simple, continuous-flow stirred-tank reactor, stirred well enough to permit assumption of uniform composition and temperature throughout the liquid volume. The desired temperature is maintained by a steam coil, and evaporation is suppressed by using nitrogen pressure. The product is fed through a heat exchanger/cooler system to a flash valve, where it is flashed to a low pressure and fed into a separator drum. In this drum, the desired product evaporates, while the sludge settles and is drawn off in the bottom liquid layer. Most of the liquid is recycled back through the heat exchanger to the stirred-tank reactor.

The figure identifies the decisions of optimization variables selected for this process-design example. In the reactor, these are the temperature T , pressure P , molal concentration of solvent C , and the fractional conversion of hydrocarbon per pass f . In the heat exchanger, we select the temperature to which the recycle is heated T_R , and, in the cooler, the temperature rise in the cooling water ΔC . Finally, in the separator drum we choose the temperature T_F and pressure P_F for the flash separation, and the residence time τ , in the liquid; the latter is needed to predict the degree of separation of the insoluble by-product. Note that these are design-type variables. We are not selecting as prime decisions the sizes of the equipment; they are an outgrowth of the process decisions which are made. Consider the fractional conversion f , as typical. Fig. 4 shows how our specified objective, the manufacturing cost of the desired product, depends on the conversion f , for fixed values of all the

other variables. Note the non-linearity, in fact discontinuity, of the objective function with respect to this variable. The breaks in the curve correspond to breaks in the available reactor sizes, the number of parallel passes through the heat exchanger system, and so forth. Important discontinuities of this type should be included and an optimization technique selected which permits their inclusion. In less-important cases, the breaks can be smoothed over, by replacing the appropriate cost curves with smoothed approximations. In our example, we have done this with the pump cost; no attempt is made to account for discrete sizes of pumps which must actually be used.

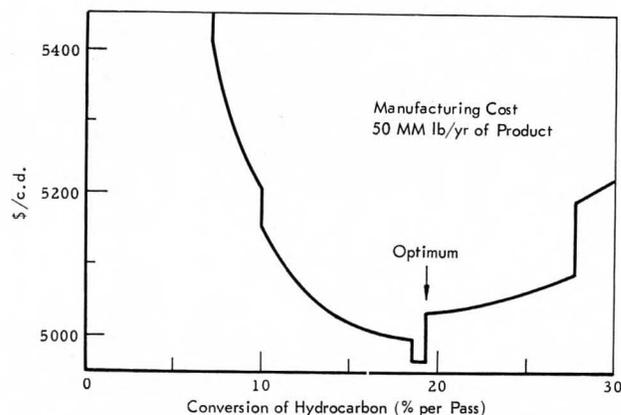


Figure 4.

2. Operations Scheduling

In addition to designing process units, chemical engineers are often involved in questions of planning and scheduling their operation. Shifts in prices, demands, and all the other problem premises almost always make operation different than was projected for the design. Moreover, in the scheduling of operations, no account need be taken of capital expenses. These have already been committed, and we are merely concerned with operating cost or profit. One example of large-scale use of large optimization models for scheduling is in the planning of oil refining operations, both in single refineries and in multi-refinery complexes. Treatment of this by non-linear methods is described by Ornea and Eldredge.²⁴

In our simple example, consider the effect of changing operations in a fixed system with a specified reactor volume, heat exchange capacity, etc. Some variables will remain the same; for example, the temperature and pressure in the reactor will continue to be control variables. However, other variables will be replaced by new ones; instead of specifying conversion, we will specify the flows of the feed and recycle streams. In Fig 5 contours of the objective are plotted as a function of these two scheduling variables. Other variables (the temperatures, pressures, and molal concentration of solvent) are held at constant values. In addition to the objective

Operating Economics

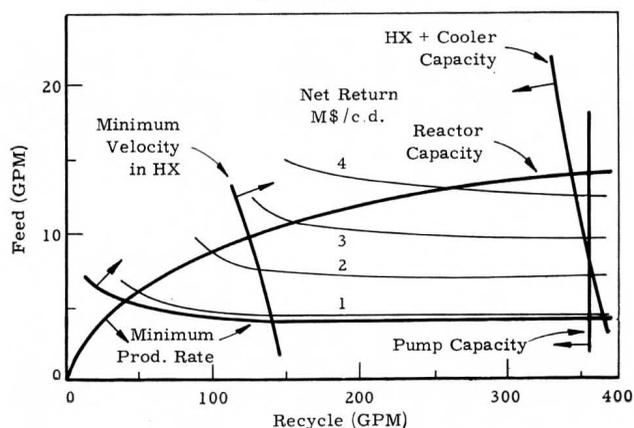


Figure 5.

function contours, we indicate various constraints coming from the physical specifications of the equipment: the capacities of reactor, heat exchanger, and pump, the minimum velocity in the heat exchanger to keep the sludge suspended, and the minimum production rate required. Note that within the central, feasible region the problem is very nearly linear. The optimum point occurs at the upper-right hand corner, where both the reactor, and the heat exchanger/cooler are operating at capacity. The near linearity of this example is illustrative of the fact that, in scheduling, we very often can obtain an acceptable description of the system in a linear programming formulation; this tremendously simplifies the optimization itself.

3. Process Control

In spite of their differences, these first two problems both involve only steady-state analysis. This is not true of the third type of problem, the control problem. Here we must account for some dynamic affects, even though it may be possible to omit consideration of short-term dynamic affects if we limit our model to the longer-period control problem. For example, our objectives often concern only temperature and concentration dynamics; then the model can neglect the effect of pressure waves or liquid-level fluctuations, as long as the specified control instruments maintain average pressures and levels at the desired point, over the period of the temperature or concentration fluctuations. For our simple example, the flow sheet illustrating the control problem appears in Fig. 6. The variables are pretty much those that are used for the scheduling operation, but we must now incorporate, in the equations describing the model, time derivatives showing the dynamic effects. In general this means that a control model formulated with the same degree of technological complexity as a process design

model will be a much more complicated model involving more complex mathematics and more difficult optimization. Fortunately for industry, the precise optimization of the control model is usually less important economically than optimization of the process design. Thus, it is usually not desirable to do as technologically complete a job on the control model as one does with the process design model. One complication of the economics for a control model is that the objective function almost invariably involves an extension in time. We are interested in costs or profits expressed as an average over a long period, and we will invariably have means of evening out our uneven operations, by the use of storage tanks or the ability to delay delivery. This makes it extremely difficult to formulate a true economic objective in terms of an immediate control variable.

(Continued on page 134.)

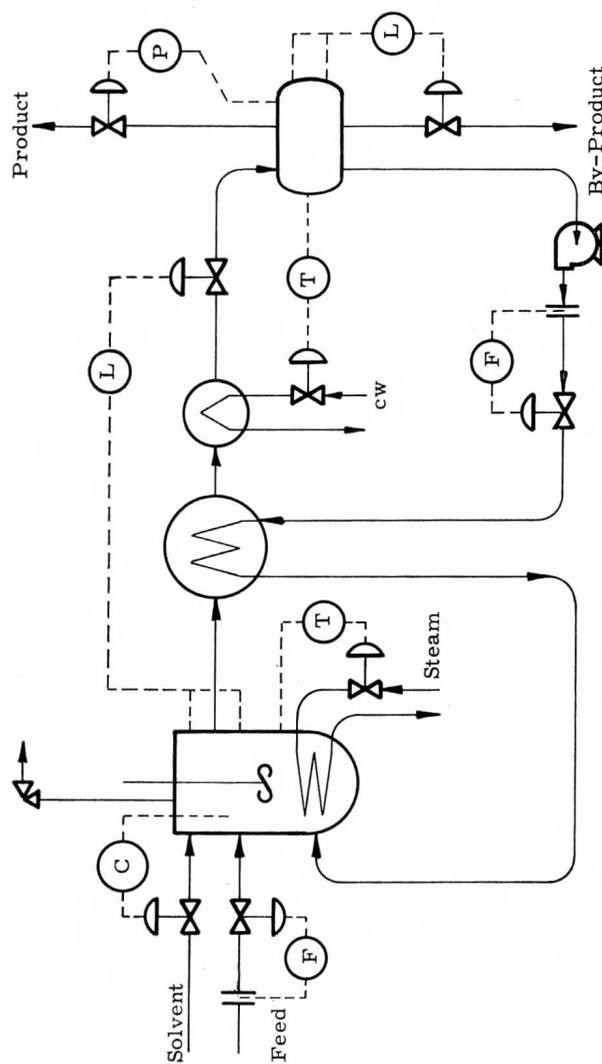
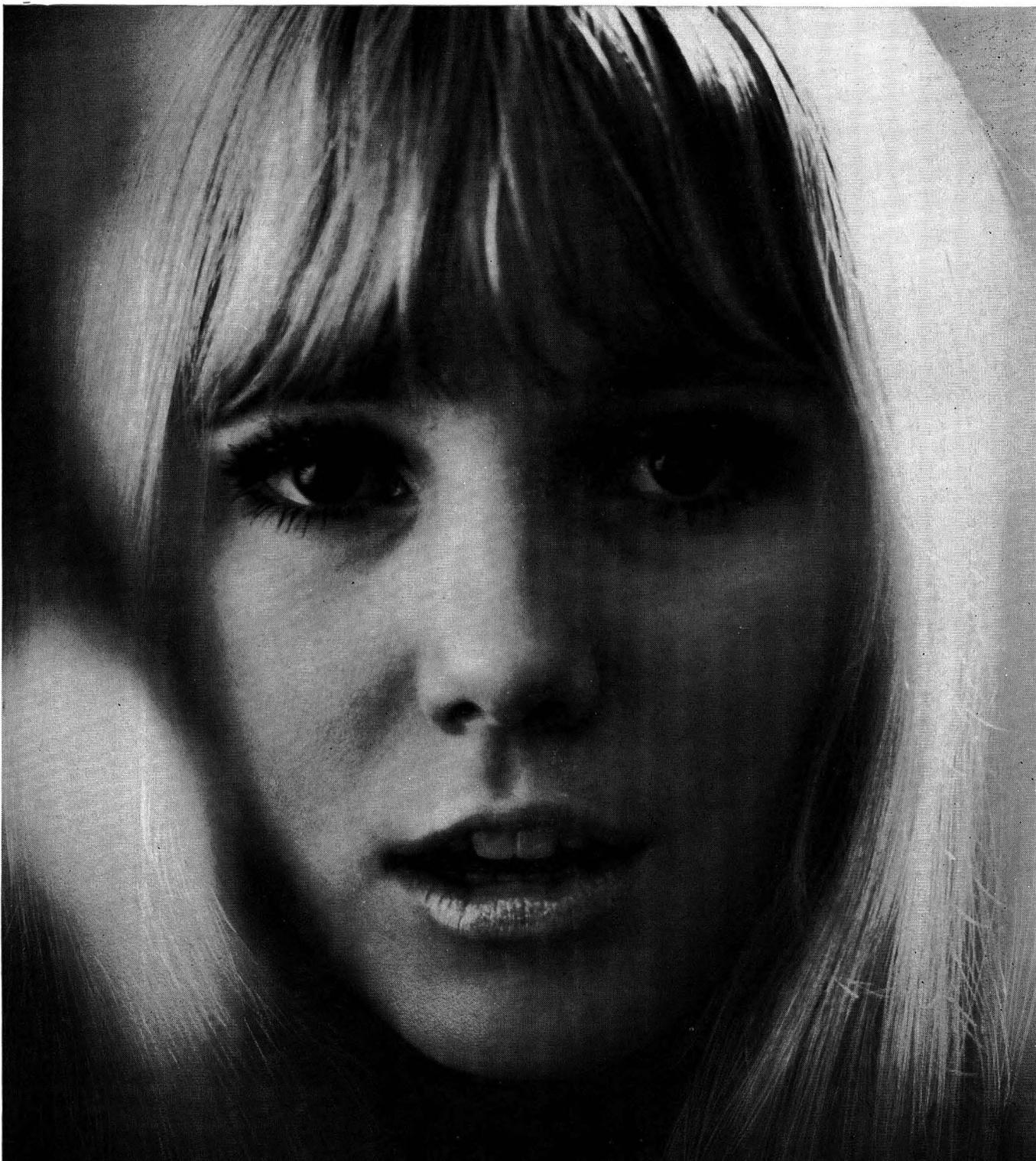


Figure 6.



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A MICROCATALYTIC TRACER EXPERIMENT

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Because of the rapid development of new analytical techniques and the increasing demands on students' time through expanded curricula, it has become necessary to streamline laboratory experiments to include as many of these techniques as possible in the shortest period of time. This report describes one of the experiments aimed at pursuing this goal in our senior chemical engineering laboratory and presents some results obtained by this year's students.

A large fraction of all industrial reactions are catalytic, and one of the most active areas in industrial research concerns the development of more active and selective catalysts for specific reactions. Although many of the early technological advances which revolutionized the petroleum industry before World War II were the result of empirical observations, the significant advances by such men as Sabatier,¹ Langmuir,² Taylor,³ Ipatieff,⁴ Emmett,⁵ and others have helped to change the application of catalysis from an art into a science.

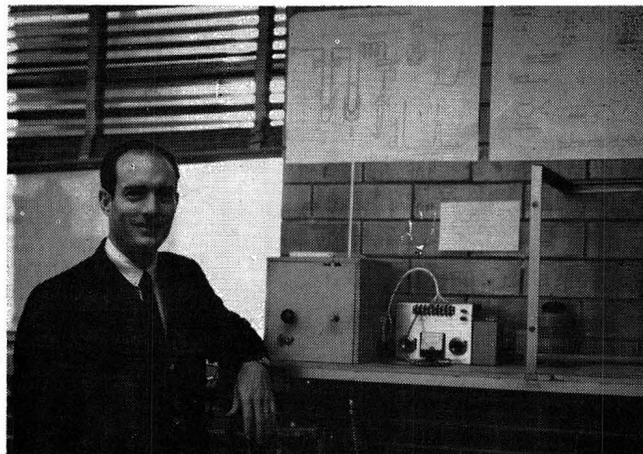
One of the standard catalytic activity tests in the petroleum industry involves the dealkylation of cumene (isopropylbenzene). This reaction seemed the logical choice for our studies over a standard silica-alumina cracking catalyst in a microcatalytic reactor for the following reasons:

It is essentially a "clean" reaction, i.e., the only significant products are propylene and benzene. There is little poisoning, which means the same catalyst can be used from day to day without reactivation. Reactant and product compounds are easily separated by GLC and are amenable to isotopic tracer investigations in a mass spectrometer. Cumene dealkylation has been used

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as a test reaction for diffusion studies⁶ and for investigations of active sites on zeolite catalysts.⁷ Cumene, an intermediate in the production of phenol and acetone, is an important commercial compound. Research involving this compound is currently under way at Rice. The entire experiment can be carried out in a reasonably short length of time.

EXPERIMENTAL

A microcatalytic reactor^{8,9} involves combination of a flow reactor with a gas chromatograph, Fig. 1. A helium carrier gas stream flowed continuously at 10 psig and about 100 cc/min through the reference side of a standard Gow-Mac thermal conductivity detector and then through a small packed catalyst bed containing a centered thermocouple well. Pulses of reactant could be injected by means of a 10 μ l hypodermic syringe through a rubber septum injection port A. The reactant was carried over the catalyst where it reacted, and the reaction products were swept immediately into the analyzing column, a six-foot coil of $\frac{1}{4}$ " copper tubing packed with silicone oil on firebrick. The separated products passed through the sample side of the Gow-Mac

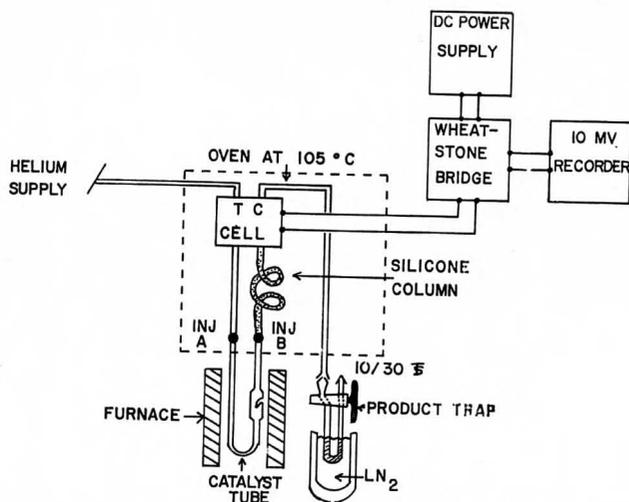


Fig. 1.—Schematic diagram of microcatalytic reactor and product traps.

detector where they caused an imbalance in a Wheatstone bridge which was recorded as a peak on a 10 mV strip chart recorder whose chart speed was 2 min/in. Calibration was effected for each compound by injection beyond the catalyst bed at injection port B. The injection ports, detector, and column were all enclosed in a transite box whose temperature was maintained near 115°C by means of a Variac which supplied power to the heating elements.

The separated products could be collected individually in a trap thermostated at -195°C (liquid nitrogen temperature) for subsequent analysis at low electron voltage in a CEC 21-104 medium resolution mass spectrometer. Helium was removed from the sample trap by evacuation at -195°C .

Pellets of commercial Houndry M-46 silica-alumina (12.5% alumina) were ground and collected between standard 20-60 mesh sieves to give particles which varied from 250 to 800 microns in diameter. Half a gram of this material was loosely packed to a depth of one cm between glass wool plugs in the 1.5 cm OD Pyrex reactor. The catalyst surface area was 270 m^2/g .

Initial activation was accomplished by heating the catalyst in flowing O_2 at 530°C for one hour to burn off carbonaceous residues, and the catalyst was then cooled in flowing helium to the 295-365°C reaction temperature range. Following this pretreatment, the catalyst retained a reproducible activity level for days without further reactivation. The temperature of the electrical resistance furnace around the reactor was controlled simply by a Variac.

RESULTS

The entire experiment was designed to cover three 3-hour laboratory periods. We have found it most effective when each group consisted of from three to six students. Our seniors were divided into five groups, with each group coming in on a different afternoon during the week to perform the same part of the experiment. This meant the whole experiment lasted three weeks. **Period I, Introduction** — During the first period, the objectives, techniques, and mathematical analysis of the experiment were described. Each student then practiced making benzene injections through injection port B until he obtained reproducible peaks on the GLC. Finally, each measured his peak areas with a planimeter until his measurements were reproducible. **Period II, Activation Energy** — A typical microcatalytic reaction spectrum is shown in Fig. 2. Besides the unde-

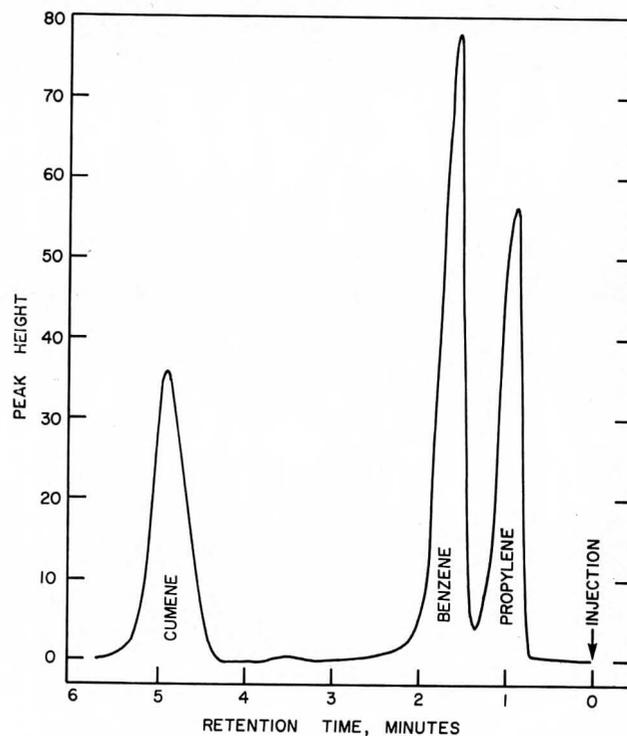


Fig. 2. — Typical chromatogram obtained from dealkylation of cumene over a silica-alumina catalyst in a microcatalytic reactor.

alkylated cumene, the only significant peaks observed were those of the products propylene and benzene. The small peak just before the cumene peak may represent a trace of the dehydrogenation product α -methylstyrene.

Conversions were determined from planimeter measurements of areas under the cumene (C) and benzene (B) peaks from the equation

$$\text{Fractional conversion} = B/(B+C) \quad (1)$$

The two compounds were assumed to have similar molar sensitivities.

Although the reaction is certainly much more complicated than this,^{6,10} for simplicity it was assumed to follow first order kinetics with no reverse reaction of products. Under the conditions used, equilibrium conver-

sion was greater than 99%, i.e., the reaction was essentially irreversible. The first order irreversible rate equation was transformed into one involving fractional conversion, x , and integrated to give

$$\ln \frac{1}{1-x} = A \exp(-E/RT)t \quad (2)$$

which can be written

$$\ln \left(\ln \frac{1}{1-x} \right) = -\frac{E}{RT} + \ln At \quad (3)$$

Since the pre-exponential factor A and the contact time t in the microcatalytic experiment are assumed to be essentially invariant with temperature, the activation energy E can be determined from the slope of a plot of $\ln \left(\ln \frac{1}{1-x} \right)$ versus $1/T$. Data from five sets of experiments on five different days by 13 seniors are shown collectively in Fig. 3; a least squares fit gives an apparent activation energy of 14.3 ± 0.9 kcal/mole. The sample size was $2 \mu\text{l}$ cumene at all temperatures in the region of 295 to 365°C .

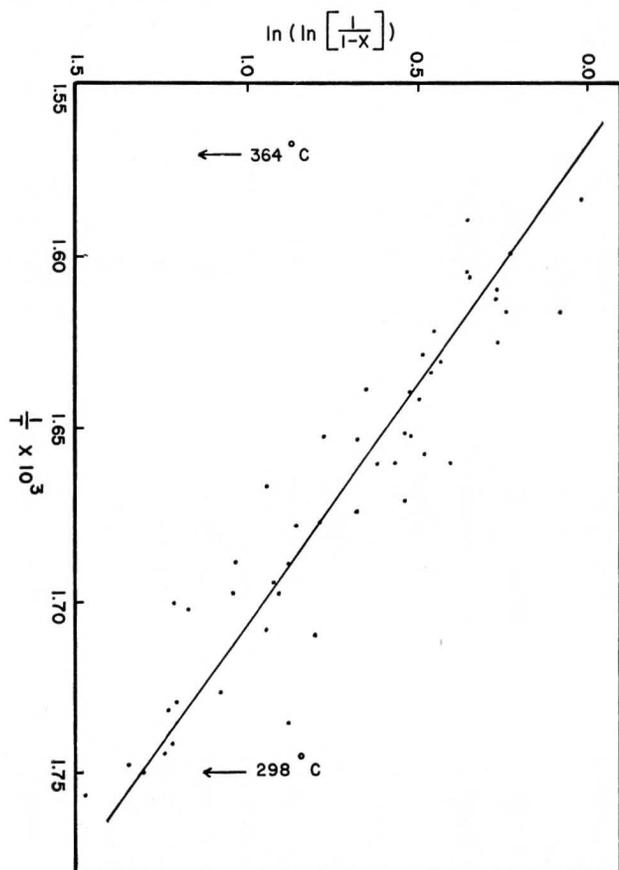


Fig. 3. — Compilation of data from 13 seniors showing temperature dependence of cumene dealkylation over silica-alumina in a microcatalytic reactor. The apparent Arrhenius activation energy is 14.3 kcal/mole.

Period III, Deuterium Isotopic Tracers — Measurements¹¹ by exchange with D_2 have shown that freshly activated silica-alumina contains about 4×10^{20} H atoms/g. These atoms have acidic properties and may provide Bronsted active sites on which the dealkylation reaction occurs. The purpose of this part of the experiment is to demonstrate participation of these atoms in several different

reactions which may occur.

When $2 \mu\text{l}$ pulses of benzene were passed over the catalyst at 340°C , there was apparently no chemical reaction, as only the benzene peak was observed in the GLC spectrum. Similarly, when perdeuterio benzene (C_6D_6) was injected, only one peak was observed. However, mass spectral analysis of that benzene peak showed that extensive exchange had occurred between the catalyst's H atoms and the hydrocarbon's D atoms.¹² Fig. 4

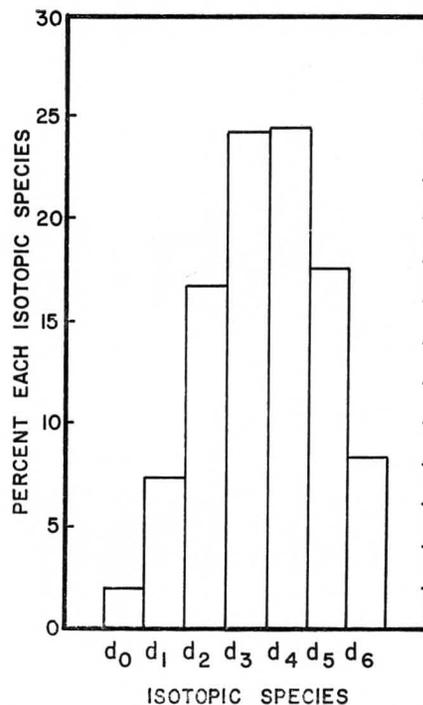


Fig. 4. — Deuterium distribution in benzene after exchange of a pulse of C_6D_6 with H atoms on the catalyst.

shows the relative amounts of product benzene molecules which contained from 0 to 6 D atoms. All peaks were corrected for naturally occurring C^{13} ; fragmentation involving loss of one or more H atoms was negligible under the low voltage mass spectrometer operating conditions used.

Seven more identical $2 \mu\text{l}$ pulses of C_6D_6 were then passed in succession every 10 minutes over the catalyst. The products were trapped and analyzed mass spectrally; the results are given in Table I. The last column showing the atoms exchanged/molecule was calculated from the equation

$$\text{Atoms Exchanged/Molecule} = \sum_{i=0}^6 (6-i) d_i/100 \quad (4)$$

where d_i is the percent of molecules containing i deuterium atoms. As the pool of available H atoms on the surface became diluted with D atoms as a result of exchange with each successive pulse, the amount of measurable exchange decreased from pulse to pulse (see Fig. 5).

From the number of benzene molecules injected in each $2 \mu\text{l}$ pulse and the average number of atoms exchanged (or "titrated") per molecule, it was possible to determine the total number of surface H atoms which were exchanged in all eight pulses. Such a cumulative

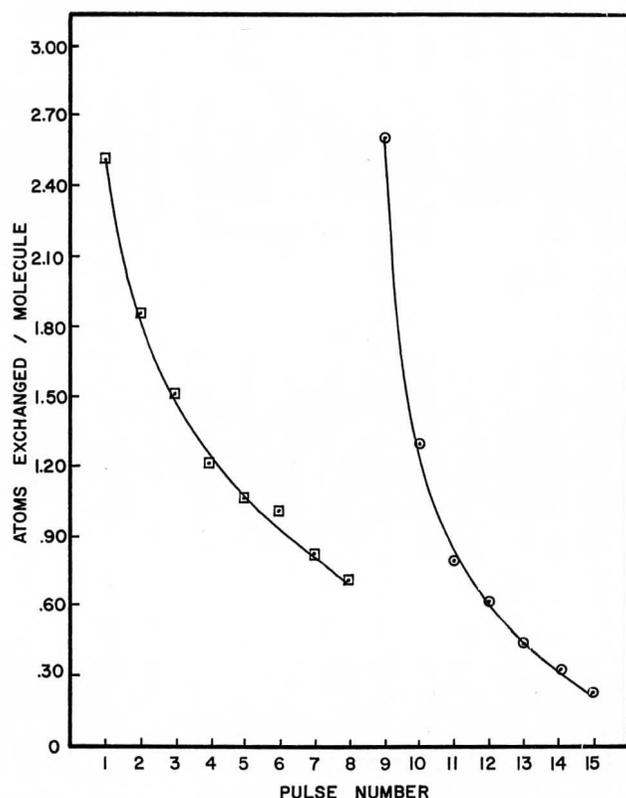


Fig. 5. — Average number of hydrogen atoms exchanged/molecule during successive passage of several pulses of benzene C_6D_6 and cumene over a silica-alumina catalyst in a microcatalyst reactor.

plot is shown in Fig. 6. A large fraction (about 75%) of the total H atoms originally present on the half gram sample underwent exchange during passage of these eight pulses of C_6D_6 .

With the catalyst now in a partially deuterated state, seven pulses of cumene were passed in succession over it at $340^\circ C$, and the conversion was constant at about 50% dealkylation. All three products were individually trapped and analyzed for pulse 9, but for the remaining pulses only the benzene peak was trapped and analyzed; the results are given in Table I. It is apparent from the results of pulse 9 that exchange was extensive in the undealkylated cumene as well as in the reaction products. In fact, to a rough approximation all the H atoms in all the hydrocarbons essentially equilibrated with the D atoms from the catalyst. For this to have been strictly true, the benzene and propylene (each has 6 hydrogen atoms) should have had the same number of D atoms/molecule, and cumene (12 hydrogen atoms) should have had double that amount using this assumption, and basing the calculation on the number of cumene molecules added and on the benzene mass spectral analysis, the cumulative number of D atoms recovered from the catalyst could be determined. The atoms exchanged/molecule were calculated from the equation

$$\text{Atoms Exchanged/Molecule} = \sum_{i=0}^6 id_i/100 \quad (5)$$

and the cumulative plot for pulses 9 through 15 is shown in Fig. 6. Most of the D atoms exchanged into the catalyst from the first eight C_6D_6 pulses were recovered in

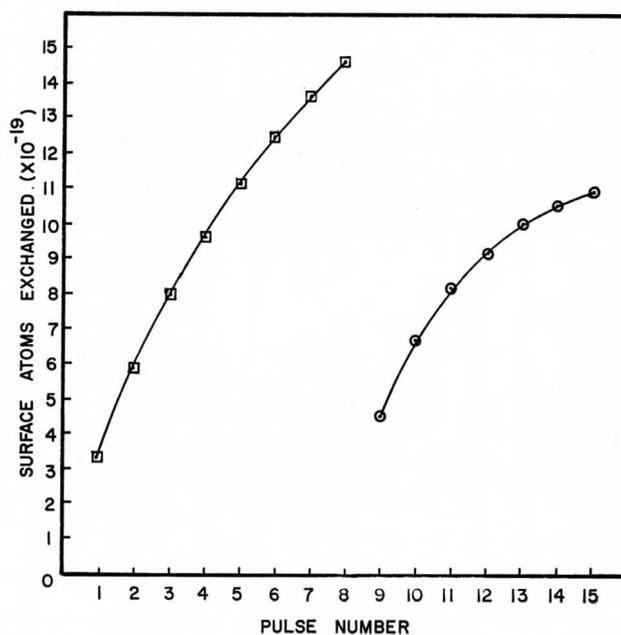


Fig. 6. — Cumulative of hydrogen atoms exchanged between catalyst and hydrocarbon during passage of successive pulses of benzene C_6D_6 and cumene over a silica-alumina catalyst in a microcatalytic reactor.

the hydrocarbon products during cumene dealkylation in the last seven pulses.

DISCUSSION

These microcatalytic tracer cumene dealkylation experiments over a silica-alumina catalyst are well suited for a senior chemical engineering laboratory. In a single integrated experiment involving three laboratory periods, the students are introduced to a wide range of concepts and techniques including catalysis, kinetics, gas chromatography, product trapping, vacuum systems, isotopic tracers, and mass spectrometry. None of the chemicals is very expensive, and the microcatalytic reactor (excluding the recorder and potentiometer) can be built for less than \$350. In our own department the mass spectrometer from the catalysis research laboratory was made available for these experiments. A research assistant was in charge of the mass spectral analyses, but the students themselves performed all other parts of the experiment.

The use of stable isotopic tracers has demonstrated that what appeared to be a relatively simple heterogeneous catalytic reaction in fact involves quite a complicated mechanism. This certainly invalidates the naive assumption of first order kinetics. Furthermore, since there was a temperature dependent peak broadening due to adsorption as each pulse was passed over the

Table I
Isotopic Composition of Products in Microcatalytic Tracer Experiments

| Pulse No. | Injected | Measured | Isotopic Composition (%) | | | | | | | | | | #D atoms molecule |
|-----------|-------------------|----------|--------------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|-------------------|
| | | | d ₀ | d ₁ | d ₂ | d ₃ | d ₄ | d ₅ | d ₆ | d ₇ | d ₈ | d ₉ | |
| 1 | B, d ₆ | B | 1.7 | 7.3 | 16.7 | 24.1 | 24.4 | 17.6 | 8.2 | - | - | - | 2.522 |
| 2 | B, d ₆ | B | 0.4 | 2.3 | 8.4 | 18.9 | 27.9 | 26.6 | 15.5 | - | - | - | 1.866 |
| 3 | B, d ₆ | B | 0 | 0.9 | 4.7 | 14.2 | 26.9 | 32.6 | 20.7 | - | - | - | 1.523 |
| 4 | B, d ₆ | B | 0 | 0.5 | 2.3 | 9.4 | 23.4 | 36.0 | 28.4 | - | - | - | 1.227 |
| 5 | B, d ₆ | B | 0 | 0.1 | 1.5 | 7.1 | 21.0 | 37.2 | 33.1 | - | - | - | 1.070 |
| 6 | B, d ₆ | B | 0 | 0 | 1.2 | 6.5 | 20.1 | 37.6 | 34.6 | - | - | - | 1.021 |
| 7 | B, d ₆ | B | 0 | 0 | 0.6 | 4.0 | 16.0 | 37.3 | 42.1 | - | - | - | 0.837 |
| 8 | B, d ₆ | B | 0 | 0 | 0.5 | 2.8 | 13.0 | 35.5 | 48.2 | - | - | - | 0.719 |
| 9 | C, d ₀ | P | 1.2 | 9.6 | 22.6 | 29.5 | 23.4 | 11.0 | 2.7 | - | - | - | 3.081 |
| | | B | 6.2 | 18.1 | 25.9 | 23.1 | 14.4 | 7.7 | 4.6 | - | - | - | 2.629 |
| | | C | 3.8 | 13.8 | 22.6 | 21.8 | 15.3 | 9.4 | 6.1 | 4.2 | 2.1 | 0.9 | 3.235 |
| 10 | C, d ₀ | B | 25.7 | 36.7 | 23.9 | 9.9 | 2.8 | 0.6 | 0.4 | - | - | - | 1.308 |
| 11 | C, d ₀ | B | 43.8 | 37.0 | 15.1 | 3.6 | 0.5 | 0 | 0 | - | - | - | 0.800 |
| 12 | C, d ₀ | B | 53.3 | 33.7 | 10.5 | 2.0 | 0.4 | 0.1 | 0 | - | - | - | 0.628 |
| 13 | C, d ₀ | B | 63.3 | 29.5 | 6.5 | 0.7 | 0 | 0 | 0 | - | - | - | 0.446 |
| 14 | C, d ₀ | B | 72.0 | 23.7 | 3.9 | 0.4 | 0 | 0 | 0 | - | - | - | 0.327 |
| 15 | C, d ₀ | B | 79.1 | 18.8 | 2.1 | 0 | 0 | 0 | 0 | - | - | - | 0.230 |

catalyst, the assumption of constant contact time at various temperatures is also invalid. These two factors were mainly responsible for the apparent activation energy being much lower than that¹³ reported in the literature over similar catalysts in a steady state flow reactor.

Although microcatalytic reactors certainly are not the best suited systems for kinetic measurements, they are extremely useful for isotopic tracer studies for several reasons:

Tracer compounds are expensive, and only very small samples need to be used in this system. It is possible to study "initial" interactions between reactants and surface after only a relatively few hydrocarbon molecules have contacted the catalyst. The method is reasonably fast.

With very few changes, this system can be modified to study the reaction under steady state flow conditions. Kinetic comparison between the microcatalytic and steady state flow systems can be made to investigate the role of diffusion in the reaction. Furthermore, the GLC is sufficiently versatile that it can be used without modification for other analyses.

The authors acknowledge grants from E. I. du Pont de Nemours and the Petro-Tex Chemical Corporation which

provided funds for development of these experiments. They are also grateful for helpful suggestions from other members of the Chemical Engineering faculty.

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THE DILEMMA OF INNOVATING SOCIETIES: Implications

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In the opening pages of his book *Ancient Europe*, Professor Stuart Piggott* introduces the useful concepts of *innovating* and *conserving societies*. He writes (p. 17): "In the one group, technological developments in the arts of peace and war must have been socially acceptable and therefore encouraged; in the other, once a satisfactory *modus vivendi* for the community within its natural surroundings had been achieved, there seems to have been no urgent need felt to alter the situation. Or again, the cultural pattern devised might be too delicately adjusted to the circumstances, and too rigidly conceived, to be susceptible of modification by technological innovation . . ." Professor Piggott's definition suggests two reasons why a community might choose to become a conserving society, and we shall explore his second possibility — that concerning the delicate adjustment of the society to its environmental circumstances—in some depth. First, however, it is necessary to say a few words about innovating societies.

THERE IS NO doubt that American Society, or at least its white, middle-class sub-society, is an innovating society. Indeed, few would deny that the scope, scale, and pace of its technological innovations — for it was technological innovation that Professor Piggott was thinking of when he wrote his definition — outstrip those of any of its contemporary societies, including the Soviet Union, Western Europe, or Japan. Many Americans take great pride in our position of leadership in technological innovation, and most Americans would reject with scorn any suggestion that the United States become a conserving society. To find support for these statements we do not even need to look beyond our own academic cloisters: the phenomenal growth of scientific and engineering research and education in the universities over the past two decades is a clear indication of the high regard for technological innovation held by the decision-making and direction-determining segments of our society. The only audible voice of dissent to the notion that the United States must remain the leading innovating society seems to come from a small but vocal group of young activists who have deci-

* Stuart Piggott, "Ancient Europe," (Chicago: Aldine Publishing Co., 1965).



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sively rejected the values of contemporary society. Unfortunately, this voice is so inexperienced, so often charged with passion, and so concentrated on highly specific issues, that it has not called attention to the basic dilemma that must bedevil all innovating societies.

This dilemma is suggested by Professor Piggott's second explanation for the origin of conserving societies. Let us recall his words: ". . . the cultural pattern devised might be too delicately adjusted to the circumstances (of its natural surroundings) to be susceptible of modification by technological innovation . . ." That is to say, the environmental resources of land, water, vegetation, minerals, energy, etc. may be so limited that technological innovations within the possibility of the restricted experience and capability of the community would upset the balance of the community's ecological situation irrevocably. For instance, a member of a hunting society inhabiting a forested region might conceive the idea that game could be driven from its cover, by selective burning in the forest, out into places where it could be easily captured. Obviously, if the territory available to the tribe

for Engineering Education

is limited, and if the tribe's rulers have a modicum of foresight and survival instinct, they will squelch this kind of innovation. A member of a modern innovating society might suggest that by further innovations (such as devices to control the area of burning or devices to defeat the tribe's enemies in war so as to enable expansion of its territory) the tribe could solve its urgent and ever-present problem: that of feeding everyone in it. Such a suggestion is not useful, however, because it ignores the point that the tribe often does not welcome such innovations, even when it is clear that they would be beneficial.

On the other hand, technological change is welcomed in innovating societies and an enormous capacity for innovation is the hallmark of present-day societies of that variety. Indeed, there may even be some individuals who hold the innovating capacity of those societies to be infinite. Be that as it may, the rate at which innovations can be made is limited, both by the total of experience possessed by the society, and by the material resources available to it. The first limitation on the rate of innovation is perfectly elementary; every student of freshman physics knows that Newton could not have invented the radio because he lived before Maxwell was born. The second limitation on the rate of innovation is also perfectly obvious to anyone who chooses to think about it. We live in a large but nevertheless definitely bounded biosphere. It has only so much lebensraum, so much sustenance that we can draw from it, so much space in which we can dump our waste matter and energy, and so much capacity for self-regeneration. We are not going to farm the moon to feed the starving billions of Asia nor can we export the surplus population there, neither can we etherally dispose of our pollution problems by packaging waste materials and firing them off to the great incinerator in the sky.

These considerations suggest that innovating societies, no matter how ingenious they may be, must eventually encounter environmental restrictions on uncontrolled innovation just as do conserving societies. Furthermore, when such restrictions become apparent, they do so at an almost unbelievable level of complexity and scale, and there is even the chance that irreparable environmental "mistakes" will have been made. Finally, though a primitave and conserving society may have the bonds imposed by its environment and its own lack of technological capacity released by contact with an innovating society, there is no higher institution to which an advanced innovating society becoming acutely conscious of environmental restrictions can turn for guidance.

This, then, is the basic dilemma of all innovat-

ing societies: **On the one hand, their institutions and ways of doing things are founded alike on a belief in the efficacy of unfettered technological innovation for social progress and a fear that without such innovation, they will stagnate and decay.** Thus, they look on conserving societies with condescension or disdain. On the other hand, they are confronted with the fact that continued uncontrolled innovation is incompatible with the material basis of life on earth; it is suicidal. Therefore, if innovating societies are not to destroy themselves, they must adopt some of the features of conserving societies; they must attempt to strike a bargain with Nature instead of simply exploiting or seeking to overpower Her; the societies must seek a material state of things that is more nearly steady than that to which their beliefs and inclinations have accustomed them.

IN WHAT SENSE MUST INNOVATING societies become more like conserving societies if they wish to survive? Not, to be sure, in the sense that they would forbid technological innovations out of a satisfaction with the *status quo* or out of a dogmatic adherence to traditional ways of doing things. What is required, rather, is a sense of proportion and priorities geared to the real needs of man and to the hard facts of his existence on this planet. Within such a set of priorities, innovations for the real benefit of humanity would be pressed with all possible speed. But innovations that are simply frivolous would be looked on with disfavor, and innovations that are destructive of the environment would be suppressed.

The practical problems of developing the requisite priorities, a mechanism to ensure their application, and means to review and revise them as needs change, are severe. This is so in large part because there exist factors within innovating societies — and within our own innovating society in particular — that militate against any slackening of the pace of technological innovation or any attempt to control its direction. These factors may be ill-defined or inarticulated but they nevertheless seem to cater to or perhaps be expressions of some deep-seated urges in our society, and they give tremendous momentum to the processes that they generate; they determine the dynamic aspects of our society.

We do not mean to imply, of course, that the dynamics of our society are determined solely by

(Continued on page 144)

TRANSPORT PHENOMENA EQUATIONS OF CHANGE

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Equations describing fluid motion and energy transport have been derived either from the Eulerian point of view of a stationary fluid element of infinitesimal volume or from the Lagrangian point of view of a macroscopic volume of fluid in motion. In the former derivations, lengthy mass, momentum, and energy balances are involved. In the latter derivations, integral transformation theorems and the Reynold's transport theorem are needed.^{1,2} The transition from Newtonian body mechanics to fluids mechanics is less than direct in both of the two derivations.

This note presents a derivation of equations of fluid motion and energy transport by considering an infinitesimal fluid element, δV , in motion. In addition to formalistic simplicity, the derivation exposes the conceptual continuity from the Newtonian equation of "body" motion to the continuum motion of fluids.

I. THE RATE EQUATION OF VOLUME DILATION

Let the mass velocity of an infinitesimal volume element δV be \mathbf{v} . The rate of dilation of δV spanned by the vector \mathbf{v} is

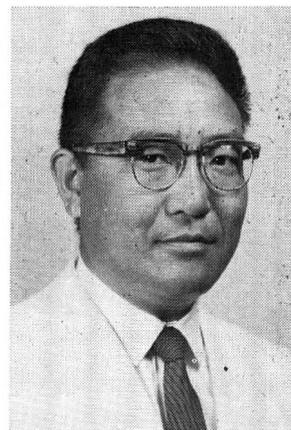
$$\frac{D}{Dt} (\delta V) = \int \int (\mathbf{v} \cdot \mathbf{n}) dS \quad (1)$$

where dS is a surface element, \mathbf{n} is a unit vector normal to dS . The integration is to be carried out at time t , over all the surface of δV , whose coordinates x_j are equal to $x_j(t)$ with $j = 1, 2, 3$. By the divergent theorem,² one has

$$\nabla \cdot \mathbf{v} = \lim_{\delta V \rightarrow 0} \frac{1}{\delta V} \int \int (\mathbf{v} \cdot \mathbf{n}) dS \quad (2)$$

Hence equation (1) can be written as

$$\frac{D}{Dt} (\delta V) = \delta V \nabla \cdot \mathbf{v} \quad (3)$$



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equation (2) expresses directly that for an incompressible fluid

$$\nabla \cdot \mathbf{v} = 0 \quad (4)$$

II. THE EQUATION OF CONTINUITY

The equation of continuity expresses the concept that δV is a closed system as to mass transfer; i.e., a "body." Let ρ denote the density of fluid, the law of mass-conservation gives

$$\frac{D}{Dt} (\rho \delta V) = 0 \quad (5)$$

Remembering $\delta V \neq 0$, differentiating equation (5) and combining it with equation (3), we obtain

$$\frac{D\rho}{Dt} + \rho \nabla \cdot \mathbf{v} = 0 \quad (6)$$

III. NEWTON'S EQUATION OF FLUID MOTION

In view of equation (5), we can regard δV as a "body" with mass $\rho \delta V$. Applying Newton's second law of motion to the "body" we obtain

$$\begin{aligned} \frac{D}{Dt} (\rho \delta V \mathbf{v}) = & - \int \int \rho \mathbf{n} dS \\ & - \int \int (\mathbf{n} \cdot \boldsymbol{\tau}) dS \\ & - \rho \delta V \nabla \phi \end{aligned} \quad (7)$$

On the left hand side of equation (7) is the rate of change of linear momentum. On the right hand side the first and the second terms are summa-

tion of forces acting on the "body" along the inward normal of its surface due to pressure and viscous tensors respectively. The last term is a force acting on the "body" with mass $\rho\delta V$ due to potential field ϕ in energy per unit mass. Noting equation (5), we can rearrange equation (7) in the form

$$\rho \frac{D}{Dt} (\mathbf{v}) = - \frac{1}{\delta V} \iint p \mathbf{n} dS - \frac{1}{\delta V} \iint (\mathbf{n} \cdot \boldsymbol{\tau}) dS - \rho \nabla \phi \quad (8)$$

Applying the divergent theorem and noting δV is infinitesimal, we obtain

$$\rho \frac{D}{Dt} (\mathbf{v}) = - \nabla p - (\nabla \cdot \boldsymbol{\tau}) - \rho \nabla \phi \quad (9)$$

Application of the integral divergent theorem to a tensor $\boldsymbol{\tau}$ is infrequent in textbooks, but its proof is not difficult²⁻³.

IV. THE ENERGY TRANSPORT EQUATIONS

The kinetic energy transport equation can be directly obtained from equation (9) by noting

$$\mathbf{v} \cdot \left[\rho \frac{D}{Dt} (\mathbf{v}) \right] = \rho \frac{D}{Dt} \left(\frac{1}{2} |\mathbf{v}|^2 \right) \quad (10)$$

Hence the transport equation of kinetic energy is

$$\rho \frac{D}{Dt} \left(\frac{1}{2} |\mathbf{v}|^2 \right) = - \mathbf{v} \cdot \nabla p - \mathbf{v} \cdot (\nabla \cdot \boldsymbol{\tau}) - \rho \mathbf{v} \cdot \nabla \phi \quad (11)$$

For the transport equation of potential energy, one notes that ϕ is a scalar point function, therefore

$$\frac{D}{Dt} \phi = \frac{\partial}{\partial t} \phi + \mathbf{v} \cdot \nabla \phi \quad (12)$$

For an energy conserving potential field, (e.g., the gravitational field), ϕ does not depend on time explicitly. Equation (12) becomes

$$\frac{D\phi}{Dt} = \mathbf{v} \cdot \nabla \phi \quad (13)$$

Multiplying equation (13) by ρ , we obtain the transport equation of potential energy

$$\rho \frac{D\phi}{Dt} = \rho \mathbf{v} \cdot \nabla \phi \quad (14)$$

Combining equations (11) and (14) we obtain

$$\rho \frac{D}{Dt} \left(\frac{1}{2} |\mathbf{v}|^2 + \phi \right) = - \mathbf{v} \cdot \nabla p - \mathbf{v} \cdot (\nabla \cdot \boldsymbol{\tau}) \quad (15)$$

Now the total energy per **unit mass** consists of kinetic energy, potential energy and internal energy, U , (per unit mass). This transport equation of total energy can be obtained by an over all energy balance on the fluid element δV

$$- \frac{D}{Dt} [\rho \delta V \left(\frac{1}{2} |\mathbf{v}|^2 + \phi + U \right)] = \iint \mathbf{v} \cdot (\mathbf{n} \rho) dS + \iint \mathbf{v} \cdot (\mathbf{n} \cdot \boldsymbol{\tau}) dS + \iint \mathbf{q} \cdot \mathbf{n} dS \quad (16)$$

where the vector \mathbf{q} denotes the **rate of energy dissipation** per unit surface area of all forms of energy including heat flux as a major form. The L.H.S. of equation (16) is the rate of decrease of total energy. The R.H.S. of equation (16) are respectively rate of work done by δV against the pressure, rate of work done by δV against the viscous friction and the rate of energy dissipation as heat. Upon differentiation and combining with equation (5) and then applying the integral divergent theorem with δV approaching to zero, we obtain

$$\rho \frac{D}{Dt} \left(\frac{1}{2} |\mathbf{v}|^2 + \phi + U \right) = - \nabla \cdot (\rho \mathbf{v}) - \nabla \cdot (\boldsymbol{\tau} \cdot \mathbf{v}) - \nabla \cdot \mathbf{q} \quad (17)$$

Since $\boldsymbol{\tau}$ is a symmetric tensor, it can be shown that

$$\nabla \cdot [\boldsymbol{\tau} \cdot \mathbf{v}] = \mathbf{v} \cdot (\nabla \cdot \boldsymbol{\tau}) + (\boldsymbol{\tau} \cdot \nabla) \mathbf{v} \quad (18)$$

Hence upon combining equations (15) and (17), we obtain the transport equation for internal energy

$$\rho \frac{DU}{Dt} = [- (\boldsymbol{\tau} \cdot \nabla) \mathbf{v} - \nabla \cdot \mathbf{q}] - \rho (\nabla \cdot \mathbf{v}) \quad (19)$$

The terms in the square bracket are rate of heat generation due to friction and rate of energy transfer to the system mainly as heat respectively. Consequently upon multiplication of equation (19) by $(\delta V \cdot \Delta t)$, it becomes of the form

$$\delta U = \delta Q - \rho \delta V \quad (20)$$

This equation is the familiar first law of thermodynamics for a closed system (i.e., a "body"). In view of the assumption leading to equation (5), equation (20) confirms the self-consistency of the derivation.

NOTATION

| | |
|----------------|---|
| \mathbf{v} | Mass velocity of fluid |
| δV | Volume of an infinitesimal fluid element |
| dS | An infinitesimal surface element |
| \mathbf{n} | A unit vector normal to dS |
| $\frac{D}{Dt}$ | Substantial derivative operator |
| ∇ | Del operator = $\left(\frac{\partial}{\partial x_1}, \frac{\partial}{\partial x_2}, \frac{\partial}{\partial x_3} \right)$ |
| ρ | Density of fluid, a point function of x_1, x_2, x_3 and time t |
| ϕ | A scalar potential function of x_1, x_2, x_3 |
| τ | The viscous tensor of a fluid |
| \mathbf{q} | Vector heat energy flux |
| v | Magnitude of fluid velocity |

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ChE book reviews

An Introduction to the Engineering Research Project

Hilbert Schenck, Jr.
McGraw-Hill Book Co.,
New York (1969)

After having directed many theses and overseen thesis direction for many years, this writer has thoroughly enjoyed reviewing this small (178 pg. 5" x 8") book.

Intended to be an introduction to the engineering research project, it moves swiftly from the selection of a topic through all the major steps to an expected acceptance of a finished manuscript for publication. The author is relentless as he points out the foibles of faculty and academic systems and is no less discerning as he analyzes student "hang-ups" which would hinder the choice and early completion of a desirable

research job. The book is written in contemporary style and should be comprehensible to both the would-be-researcher and his director.

Analyzing the volume in more detail, the reviewer believes that "The Selection of a Project" covers the field well but probably ascribes somewhat more than a normal amount of initiative to a student. Unfortunately the conception of a project more frequently falls on a faculty member than on a student and therefore Chapter 2, "Sources for Project Ideas" (25 pages), is far too long. However the short and meaty "Project Check Sheet" should be noted by everyone.

The chapter "Searching the Literature" attacks the subject with clarity, vigor, and decision. It quickly covers the usual but needed generalizations but follows them up with a well conceived and highly possible case history.

How many times have projects failed for lack of apparatus, time, or cost planning? Here is an author who believes in these efforts as an integral part of the project. Indeed he stresses these activities not only as highly desirable but even mandatory if a real researcher and a satisfactory project are to be produced. His tips are pertinent, timely and frequently annoyingly discerning. Unfortunately the author chooses to elaborate next on his categories of research—an area which he could better have omitted—for although his discussion of "Digital Computer Studies" is a good short approach to a long problem, his "Pedagogical Studies" and "Design and Systems Areas" are far below his overall standards.

In his last two chapters on "Reports" and "Journal Papers and Meeting Presentations" the author has been appropriately and pleasantly brief. He has obviously called upon many experiences, both sad and glad, and has extracted an essence which combines philosophy with practicability.

There is much in this book for new researchers to learn before sad experiences can dishearten or even remove them completely from the field, but the book also may be a gage for a more experienced researcher or research director to recheck his effectiveness.

Surprisingly despite the "heavy" material contained in this book, the style is light, friendly and interesting; it is to be hoped that the experimental project reports will be, too!

Gordon C. Williams
University of Louisville

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A SELF-PACING, AUTO-GRADED COURSE*

G. DAVID SHILLING
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INTRODUCTION

A two-credit course in reactor engineering, required for senior students in Chemical Engineering at the University of Rhode Island, has for the past three years been operated in an auto-graded mode (so called because the student supposedly decides what grade he will get.) Because the senior classes are not large, only one section of the course was scheduled each year, and all the students participated in this experimental program. Except for three graduate students, the students have all been seniors. A wide range of scholastic achievement levels has been represented — from students headed for graduate school, down to some on the verge of being dismissed.

The goal of the experimentation was to find a way out of a situation where the instructor met two hours a week with a well-knit little group of tired students willing to let him do all the talking and most of the work. It was hoped that by using the auto-graded mode, which was described in ASEE Publications, first by Norman Balabanian¹ and then by Roland Mischke², the more ambitious students could be released from the lock-step pace and the dependence on the instructor; and by requiring each student to take the initiative for his progress toward a passing grade, the less ambitious students would be confronted with some facts of life.

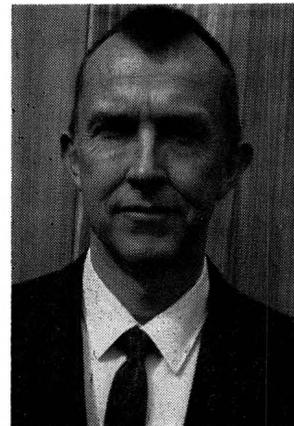
DESCRIPTION OF COURSE

The rules governing the operation of the course are shown in Table I, the "Course Plan" which was distributed to the students at the beginning of the course. A student's progress through the course is marked by his passing a series of tests, and his course grade is determined by the number of tests he passes (eight for an A, seven for a B, etc.). Each test "covers" one chapter in the textbook by treating in detail a set of problems illustrating the principles set

¹N. Balabanian, "Removing Emphasis on Grades," *J. of Eng. Ed.*, 54, No. 7 (March 1964).

²R. A. Mischke, "A Semitutorial Approach to Teaching," *J. of Eng. Ed.*, 56, No. 3 (November 1965).

*Presented at the Annual Meeting of ASEE, June 17-20, 1968.



G. David Shilling is a graduate of the University of Delaware and the University of Wisconsin (PhD '50). He taught at Kansas State and is now completing his seventeenth year on the URI faculty. He developed an interest in process control at summer institutes at Case Institute and the University of Colorado and published *Process Dynamics and Control* in 1963. Since his participation in the ASEE's Programmed Learning Project (1965-66), he has experimented with programmed instruction and self-paced and auto-graded courses.

TABLE I — COURSE PLAN
Chemical Engineering 64 — Fall 1967

The text book will be *Chemical Reaction Engineering* by Octave Levenspiel.

The instructor will select and announce a set of problems for each chapter as follows: Chapters 2, 3, 5, 6, 7, 8, 14, 13.

A student will obtain credit for a chapter by scoring 90% or better on a written examination on the chapter. Only then will he be eligible to take the examination on the next chapter, in the order shown above.

Examinations will be limited to 55 minutes. They will be given at 1 P.M. on Monday, Wednesday, and Friday, between September 21 and January 13, school holidays excepted.

The instructor will retain all copies of the examination papers and questions. A student may see and discuss his examination paper when convenient.

A student's course grade will depend on the number of chapters he passes as follows: eight, A; seven, B; six, C; five, D.

forth there. These problems are much more involved than a student could be expected to work "from scratch" in an hour examination. But the students are given the problems in advance and have worked them and perhaps discussed the solutions with the instructor and other students.

It is assumed that each student will choose what course grade he will get and decide when he will pass the required tests for that grade. To help the student pace himself through the semester, he is given a copy of the "Experience Table" for last year's class. The table shows that it is

not unusual for a student to take a test two or three times before achieving the high-quality performance required for passing (90%). The tests are so comprehensive that, in order to score 90%, a good mastery of the material covered in the chapter is needed, even when the student has taken exactly the same test a few days earlier and afterwards discussed his errors with the instructor.

In the beginning of the experiment (Class of 1966) class meetings were held as scheduled. But it soon became apparent that the students were getting "out of step," so that too few students were finding any given topic sufficiently pertinent to the work they were doing (or putting off) to make class meetings fruitful. After six weeks of regular class meetings with steadily decreasing attendance (since no effort was made to coerce attendance) no more such meetings were held, although some extemporaneous lectures were given to small groups. With the Classes of 1967 and 1968, class meetings were discontinued as soon as the students voted to use the auto-graded mode. The most efficient plan would probably be to hold class meetings for the first three or four weeks, while the students are relatively "in step." But the students find the no-class feature one of the big attractions of this mode of operation. Some of the disadvantages of not having formal class meetings may not have showed up in this experiment, because nearly all the students were also enrolled in a laboratory course which met six hours a week with the same instructor. So there were many opportunities for student-instructor consultation.

The advantages and disadvantages observed in the operation of the course are discussed later.

COURSE EVALUATION

A course-evaluation questionnaire was filled out by the students at the end of the course. The returns were anonymous and it appeared that the students felt quite free to express their feelings and suggestions. In 1966 there were seven returns from a class of ten, and in 1968, nine from twelve. In 1967 the students got away before the questionnaire session could be arranged. For the two classes covered, the total enrollment was 22 and the number of questionnaires completed was 16.

Table 2 summarizes the answers obtained. To encourage the students to think about each question, the answer blanks on the questionnaire were scrambled as to positive, neutral, and negative reactions. In Table 2, the answers have been rearranged for easier analysis.

The two classes are not tabulated separately because they did not differ greatly in their opinions. The Class of 1968 indicated a somewhat more positive attitude: surer of mastery of the

TABLE II — COURSE EVALUATION
QUESTIONNAIRE

| Questions | Answers | | | Suggested Number Checking |
|--|--------------------------|-------------------------|------------------------|------------------------------|
| | <i>yes</i> | <i>perhaps</i> | <i>no</i> | |
| Do you feel that the material covered in this course will be of value to you in your career? | 8 | 6 | 2 | |
| Did you find the course work interesting? | <i>most of it</i> 9 | <i>some of it</i> 4 | <i>little</i> 3 | |
| Did you feel that you have a good understanding of the material? | <i>most of it</i> 9 | <i>some</i> 7 | <i>little</i> 0 | |
| How did the amount of material covered compare with other two-credit courses? | <i>too much</i> 11 | <i>average</i> 4 | <i>too little</i> 1 | |
| What do you think of the text book used? | | | <i>yes</i> 8 | <i>no</i> 6 |
| | interesting | | 11 | 3 |
| | easy to understand | | 14 | 2 |
| | well organized | | 3 | 12 |
| | too condensed | | 1 | 10 |
| | too varied | | | |
| How did you feel about this course plan at the beginning of the semester? | <i>enthusiastic</i> 5 | <i>willing</i> 8 | <i>reluctant</i> 3 | |
| How would you feel about it now? | <i>enthusiastic</i> 0 | <i>willing</i> 14 | <i>reluctant</i> 2 | |
| How well do you think this plan would work on various class levels? | | <i>well</i> | <i>poorly</i> | <i>average</i> |
| | Soph | 0 | 12 | 4 |
| | Junior | 1 | 5 | 10 |
| | Senior | 7 | 3 | 6 |
| How well did the problems assigned cover the important material in the book? | <i>well</i> 5 | <i>pretty well</i> 9 | <i>poorly</i> 2 | |
| How well did the exams test your mastery of the problem topics? | <i>well</i> 5 | <i>pretty well</i> 8 | <i>poorly</i> 3 | |

material and of its career value, less critical of the textbook, and not so impressed with the excessive amount of work demanded. On the other hand, they felt more keenly the danger of "putting-off" work, and were more critical of the tests. This modest improvement in attitude, displayed by the third group compared to the first group, may be in part due to more experienced handling of the course by the instructor. Also, the third group had two outstanding students and a well-developed group spirit.

DISCUSSION

The amount of material covered in this course varies from student to student. ("A" students study more chapters than "B" students; "B" students more than "C" students, etc.) because

TABLE II — (continued)

Check any of the statements below which represent fairly closely your experience in this course:

| | Number Checking |
|--|-----------------|
| I spent a lot of time studying the text book on the topics covered by the problems. | 12 |
| I read the whole chapter carefully. | 8 |
| I also read some chapters not covered. | 2 |
| I tended to ignore the book and get problem solutions from other students. | 5 |
| I did the problems mostly on my own and really understood them. | 11 |
| I tried to memorize the problem solutions instead of understanding them. | 5 |
| I felt that having the course organized this way saved time for me and let me do my best. | 5 |
| I expected to pass more exams, but found the latter chapters were too hard or took too much time | 3 |
| It was easy to put off working on this course. | 12 |
| I would have done better if there had been some deadlines at (monthly) intervals. | 6 |
| I didn't like having to plan my own work. | 2 |
| I felt that some students had an unfair advantage. | 5 |
| The instructor didn't seem to care whether I worked or not. | 8 |
| The instructor was not very helpful when consulted | 3 |
| What factors hurt exam effectiveness? | |
| too easily memorized | 6 |
| not enough time | 4 |
| asked wrong things | 2 |
| hard to interpret | 2 |
| students cheated | 2 |
| too mickey-mouse | 1 |
| poor surroundings | 0 |
| too much time allowed | 0 |
| Write-ins (one each): | |
| had to be memorized | |
| many topics not covered | |
| had to memorize numbers | |
| rather picayune | |
| too much detail in correction | |

this seems to be the simplest way to organize an auto-graded course. This disadvantage would be harder to accept if the course were not at the end of the curriculum. On the other hand, comprehension level is maintained high for all students ("90%"). In the conventional, lock-step course, there is a standard "coverage" and the students are graded according to their comprehension level. Actually, both plans have arbitrary limitations: 90% is not perfect, and there are always more topics which could profitably be included in the standard coverage. For many a student, the feeling that he has achieved high-level com-

mand of a topic would be a welcome change from the feeling of failure or mediocrity he gets in many of his courses. It is certainly more realistic training for engineering practice to develop a comfortable facility with a limited subject area than to get a haphazard acquaintance with a broader field. The coverage achieved in this course is considered by the author to be excellent for the two semester-hours credit given. Of the 34 students who have taken the course, only four (grade D) have stopped short of consideration of optimum-temperature progression in homogeneous reactors (C-level), while thirteen (A and B), also got work in heterogeneous reactions.

Retention of skills developed is, of course, as important as developing and demonstrating these skills. As in the usual educational situation, no measurement of retention was here attempted. However, the instructor was sensitive to indications of retention observable during a laboratory course the students take in the semester following the kinetics course. The observations have been favorable: when these students were assigned lab problems related to reaction kinetics, they showed quick recall of relationships, procedures, and even some details. Their attitude suggested confidence in their ability to handle this subject matter. It is reasonable that retention of skills learned in this type of situation would be relatively high, because the student has to "dig it out" for himself, and because, before leaving each unit, he is assured that he has a good grasp of the material.

The problems chosen by the instructor for the students to work on need to be "comprehensive," i.e., requiring a good grasp of the entire subject area to be "covered." It is not cricket to require the student to show more on the test than he had to do to solve the problems. On the other hand, the problems do not have to be neat and limited; the students have time to chew them over, seek out additional data, and resolve ambiguities (as in engineering practice). Some "old" problems can be used, since it is not essential that each student work every problem entirely on his own. This year, about half the problems in each set were new, and the rest were taken from previous years' sets. Some students attempt to memorize problem solutions borrowed from other students or found in "files" left by earlier students. However, students have testified that this approach is not successful. The problems are so involved that it is very difficult to write a 90% test without understanding the solution.

The tests need to be comprehensive enough that the student must either work through the problems himself or thoroughly study the solutions he borrows. The questions do not have to be pared-down to what an average student can

reasonably be expected to work out in 55 minutes. The student works on the problems before the test and he can take the test a second or third time if he has trouble assembling and organizing his answers in 55 minutes. So, even ambiguities in test questions, though to be avoided, do not have tragic consequences.

Repeated tests are not composed in the familiar "sampling" mode. This would result in students using information about the test questions as a guide to slighting important parts of the topic to the "covered." A typical test is shown in Table 3. Students are asked to show parts of

TABLE III — TYPICAL TEST

Exam on Chapter 5— Fall 1967

1. For Problem 11 (see problem statement below), derive the differential equation relating reactor volume to fractional conversion, and show the computations of the values of the constants used (in the integrated form of the equation) to find k from the experimental data.

2. For problem 18, derive the differential equation relating volume of reactor to fractional conversion, and explain how you proceed to compute the volume of the required reactor.

3. For Problem 19, derive the required equation and show all computations for the volume of (only) the back-mix reactor.

(Problem statements followed.)

some problem solutions in detail, while for others, they are asked to describe how the problem is solved. Students are often required to show the source of a model equation. This they refer to as "memorizing derivations," which they consider unfair. They also find that they can best get through a test in the limited time if they memorize a few key numerical values. Although many complaints result, it is doubtful that there is any lasting resentment. Students are so used to cramming for exams, that to memorize, ten minutes before a test, a few simple things is not much strain. The requirement that a test failed must be repeated in its entirety is the cause of the most-often expressed student irritation.

The repeated-test feature produces a steady stream of tests to be graded, and grading often must be done with unusually high precision, in order to decide between a 91 and 89 without seemingly arbitrary or inconsistent. Of course, a test paper which has two really bad flaws can be checked off quickly, as can a well presented repeat test by a student who nearly made it last time and has been shown his error. It is even more essential than in conventional courses that tests be graded promptly — within 24 hours at

the most. This may require some careful planning by the instructor, such as limiting the time when tests are given so that he is free to correct them immediately. No "final exam" was given in this course, as there seemed to be no role for it.

The role of the instructor in an auto-graded course is different from that in a conventional course. It is expected that the student will think of the instructor as a source of useful information. The instructor can promote this attitude by giving out hints and checking students' problem solutions, as well as by explaining mistakes on tests. This consultant role contrasts with the need a student sometimes feels to "snow" his instructors (impress them with his knowledge while not revealing gaps in his command of their subjects.) The instructor of an auto-graded course is in a good position to find out what a student needs help on, and what he can do on his own. In order to use this opportunity effectively, the instructor needs a firm grasp of his subject matter and the ability to listen to students. When meeting a rapid succession of students with questions on a wide range of topics, he has to "shift gears" a lot. If they come in groups, he may find himself operating in a "time-sharing" mode.

When the instructor finds himself treating the same, often trivial, question over and over as each student comes upon it, it occurs to him that if he were giving a lecture course he would need to discuss the point only once. He can minimize his losses here by individualizing these encounters and using them to build up rapport. For topics that are sure to cause trouble for a lot of students, a mimeographed hand-out can be prepared. With the excellent textbook used in this course, only one such text supplement has been prepared. (It deals with the question of changing density of the reaction mass in a flow reactor.) The instructor of an auto-graded course spends more time "consulting" with students, but less time preparing and delivering lectures (and wondering if he is "getting through" to the students.)

The auto-graded course rather than promoting competition between students, stimulates the formation of study groups. Leading students get considerable opportunity to help other students, and strengthen their own learning in the process. A certain amount of working together on problems is good training for engineering practice, and in an auto-graded course, is not the threat of the instructor that it sometimes is in conventional courses.

The effect of this course format on a student's motivation is of course difficult to generalize. Ostensibly, the student is working for a grade and whatever that means to him. Although this does not sound very commendable, perhaps in the

present-day college context it is not in any real sense a regression. And, it would seem that it would help a student focus his energy to know that the grade he chooses is his when he demonstrates the required learning. The students indicated on the course-evaluation questionnaire that they put more effort into the course than they would expect to put into a two-credit course.

The pressure on the student in this course was rather even and continuous, compared to conventional courses, where there are sharp peaks before six-weeks exams and low periods between them. This low-tension atmosphere, while it was an advantage for some students, was the most important factor limiting the general success of the course. Many students put off working on the course so much that they came out with C-level achievement where they could, with wiser investment of their time, have attained the A level. (Some of these students may have been waiting for their leaders to move, and when they did move, couldn't keep up.) To combat procrastination, the instructor supplied each student with an Experience Table at the beginning of the course, and offered additional copies occasionally. He also drew attention to the deadline established for the end of testing. (This deadline was extended for one student because of illness and for one who was working hard on a D.) More effective ways of reducing student procrastination are still being sought.

The self-pacing feature, which permits procrastination, is on the other hand a strong motivating factor for some students. They are very impressed by the prospect of finishing the course well before the end of the semester which is entirely possible and has been done by some students.

Undoubtedly a lot is gained, in the way of good feeling about the course, by the freedom from weekly schedules, class attendance, and the final exam. Of course, one can not say how much this

pays off in faster, more lasting learning. If most courses were self-pacing, the advantages of novelty would fall to the lecture-exam courses. Ideally, the different courses in a curriculum should be operated in a wide variety of formats, each in an optimal way for its particular objectives. Cheating is not an important factor in this course, because the test questions are not secret and tests failed are repeated without significant penalty, nor is any advantage gained by not giving credit for help received. Ethical problems are raised by a largely undesirable behavior pattern known as "leaching," where an unconfident student will attach himself to a leader, or one with a channel to a leader, in order to obtain more information about the problem solutions than he is able to contribute. There is little the instructor can do about such a situation. The students tend to work out arrangements so that all involved gain something.

CONCLUSIONS

All the students in this auto-graded, self-pacing course demonstrated high-quality command of a reasonable amount of chemical-reaction-engineering skills. There were no failures, and only one early drop out. Forty percent of the students received A or B grades for work beyond the level considered satisfactory for the number of credits given. There is every reason to believe that their retention of this learning will be superior. The amount of material covered varied with the student, and would have been greater for some if the tendency to procrastinate had been suppressed. Students generally agreed that they worked harder than in most courses. A theoretical advantage of the course is that the student behavior encouraged (if not uniformly obtained) bore a strong resemblance to that of a practicing engineer.

OPTIMIZATION R. R. HUGHES

(Cont'd from p. 116)

4. Equipment Design

The final category is really just good equipment design. To obtain detailed pictures of the makeup of packed bed reactors, the nature of internal baffles in stirred tanks or the exact form of heat exchanger bundles, a good designer must optimize in terms of some minimal cost or maximum-performance criteria. Each type of equipment requires its own special treatment for optimization, so that a general treatment of equipment optimization is not really desirable. In many cases, however, it may be possible for the designer to make use of some of the optimization algorithms.

MODEL FORMULATION

How then do we go about formulating a process design model? The calculations normally involve six distinct steps, once the desired decision variables have been chosen and the necessary objective and constraint functions have been identified.

- **Stoichiometry.** The heat and material balances for all major pieces of equipment are normally involved in any process design. According to the problem, it may be desirable to make the material balance on a mole, weight, or volume basis. In some cases, for example in certain types of refinery problems, it may be possible or necessary to treat the stream in total. But, normally, at least a nominal set of components should be identified and separately balanced.

• **Chemistry of Conversion.** For conversion processes, some sort of chemical description is needed. In a few situations, chemical equilibria may be adequate. Generally, however, at least in some simplified form, there must be a treatment of the chemical kinetics. Which-ever treatment is used, the equation should apply throughout the region of interest. If necessary, new constraints should be formulated to eliminate areas of ignorance with respect to the chemistry. If these constraints are significant at the optimum point, it may be desirable to do further developmental analysis work in order to amplify the kinetics, or the chemical equilibrium.

• **Thermodynamics of Separation.** For a separation process or the separation units in a larger process, some representation is needed of the thermodynamics of the separation, the phase equilibria and volume and enthalpy changes.

• **Equipment Sizing.** To relate the stoichiometry, chemistry and thermodynamics of the process to the actual process plant, equipment sizing calculations are needed. In some cases, these will be nothing more than arbitrary rules; in others they will be capacity or performance correlations. This step is often the most uncertain, and may require formulation and reformulation as the region of interest is identified.

• **Capital Cost Estimates.** Once the equipment is sized, a cost estimate must be developed for it. Usually the detailed cost estimating methods suitable for a final contract bid are not necessary. Instead we need approximate methods that show how costs vary with small changes in equipment size. Happel's book¹⁵ contains many useful tables and equations of the type needed.

• **Economics and Accounting.** The accounting equations must be combined with capital cost amortization to produce an economic balance for the process. Normally the objective takes the form of some rate-of-return, payoff time, or the like. Happel's book¹⁵ describes some of the mathematics involved, but the best review of the proper economic objectives is given by Souders.³⁰

SOURCES FOR EQUATIONS

To obtain the desired model equations we can use several different sources. First (and often overlooked) are the definitions, e.g., the molal concentration of a component, the average enthalpy of a stream, etc. Then there are first principles, like the conservation of mass, the laws of thermodynamics, the formulation of economic objectives and the like. The mass of chemical engineering knowledge usually appears in the form of established correlations, such as the dependence of the Fanning friction factor on Reynolds number and pipe roughness, the capacity of packed bed contactors, the heat transfer coefficients in contact with a fluid bed, and many, many more. Finally, if general correlations cannot be found with sufficient reliability to describe the desired application, we must have recourse to experiment. If the optimization study is di-

With (the many methods available), further extensive work on . . . optimization algorithms does not seem worthwhile for the engineer.

rectly involved in the guidance of development work, we must keep the experiment to the minimum necessary to satisfy the desired goal of design optimization. At the same time, we must keep in mind what the outcome of a successful calculation might be, a detailed design of the final plant. If this design will be called for immediately upon obtaining a satisfactory result from the evaluation process, then a short cut in experiments may lead to slowing down design.

SIMPLIFYING THE MODEL

The optimizer must keep in mind that his mathematical model should be as simple as is consistent with the problem. At times, a very complex model is needed, when a very precise answer is desired and justified. But many process evaluations and most preliminary process designs can be done with a greatly simplified model. It must be remembered that the final design obtained from an optimization consists of a set of design variables, the best possible set. Once these have been identified, it is possible to produce a much more refined design which will provide all the necessary engineering detail as well as checking the estimated objective function and the specified constraints.

Here are a few points which can be checked to see whether a model satisfies this goal of simplification:

• **Use estimates or "average values" whenever these are adequate for the purposes of the problem.** Just because an engineering correlation exists for a given piece of equipment does not justify inclusion of this correlation in a model. For example, detailed correlation of heat transfer coefficients versus heat exchanger design parameters and throughput is merely wasted, if the heat exchanger does not play a crucial economic role in the overall design. Here, it is much better to use merely an average heat transfer coefficient, estimated from good practice, and a simple cost estimation as a function of the square feet of exchange surface required. Another example is the use of approximate over-all absorption-factor equations to represent performance of an absorber peripheral to the main process, in preference to a detailed tray-to-tray calculation, even if the latter is readily available, along with the necessary vapor-liquid equilibria to permit its use.

• **Group like components in the material balance.** Most chemical processes contain enough chemicals to make the identification and separate calculation of all components difficult. Unless their separation is crucial to the process,

isomers and other like groups of components should be treated as single components. Nearly all chemical engineering correlations of separation equipment involve summations over the components, so the number of components identified should be minimized. This applies also to kinetic models. Here, each additional component involves at least one additional kinetic constant, and often several. The kinetic model for the process study is merely a **representation** of the kinetics. It is not a true scientific explanation of the chemistry. This should be kept in mind while developing the model. If necessary, additional constraints can be added to limit the region of applicability of a given equation, and insure that undesirable extrapolation does not occur.

- **Use a good base case and consider marginal changes from this base case.** In many cases this technique will lead to a much simpler model, since first or, at most, second-derivatives are all that need be included. At other times too broad-brush a treatment of marginal affects around the base case may completely vitiate the study. Finding the proper balance is part of the business of being a good engineer.

- **Correlate results of detailed study of units or sub-units of the main problem.** This ties in with the base case method discussed above. Even when the base case approach is not valid for the problem as a whole, it may be used for certain parts of the problem. For example, in the treatment of an oil refinery, it may be possible to describe the performance of the gas-recovery unit for the catalytic cracker in terms of a few crucial composition variables and certain major decisions as to recovery of key components. Then a series of detailed tray-to-tray calculations could be used and correlated to predict expected costs and predicted separation performance, in terms of the key variables.

- **Use the simplest acceptable equations to describe directly-related experiments.** If the optimization is being used to guide development work, there will be directly-related experiments which can be used to update the model. In a sense, these experiments appear, to the model, just like the results of separate studies described above. Elaborate analysis of the experimental data is only necessary if extrapolation is essential in order to produce the desired optimization. In most cases, a simple response-surface-type equation may serve the purpose. However, some thought should be given to choosing the right form of the variables; for example, a logarithmic variable should be used wherever these are more significant physically than arithmetic ones. However, the statistical significance of the experiments is rarely sharp enough to allow greater than a second-order response surface.

USE OF PROBLEM STRUCTURE IN OPTIMIZATION

Optimization problems can often be handled more easily by taking advantage of the structure of the problem. In the first place, the mathematical form of the resulting equations may play a significant role in terms of the ease of optimization. If these equations are all linear or can be linearized without excessive distortion, the powerful techniques of linear programming can be

used. If they are non-linear but continuous or have, at most, a few discontinuities, non-linear programming or optimum-seeking algorithms may be used. However, if these discontinuities are extensive or if the discrete nature of some decision variables must be considered, then the problem becomes much more difficult; in principle, it requires use of integer programming, where perfectly general methods for large problems are not yet available.

On top of this *mathematical* structure is the *logical* structure of the problem. Many linear problems fit into the so-called transportation model, which corresponds to the problem of finding the minimal-cost policy to supply a number of demands at varying locations, by a number of different factories with different capacity limits. This is one of a number of network problems considered, among others, by Ford and Fulkerson.⁸ Some integer problems can be fit into the travelling-salesman or knapsack forms, for which general methods of approach exist. Many process problems occur in staged or cyclic form, and can be subdivided by techniques described by Rudd and Watson²⁸ and by Aris, Nemhauser and Wilde.² Finally, problems that are sequential or repetitive in nature, such as the multi-period planning problem, can often be formulated, and sometimes optimized, in a way that takes advantage of this repetitive structure. The Partition Programming algorithm described by Rosen²¹ and used by Ornea and Eldredge²⁴ is readily adapted to this sequential problem, or to the natural partitioning which occurs in large-scale scheduling problems.

CHEOPS — A CHEMICAL ENGINEERING OPTIMIZATION SYSTEM

In an earlier paper¹⁸ we described a system of programs termed CHEOPS, which takes advantage of the general structure of process problems. Fig. 7, taken from this paper, shows how a modern refinery falls into units with information flow between units confined to the process streams connecting the units. Even if a detailed design of one of the units is considered, this same sub-division is possible. Fig. 8 shows what happens to the vacuum flasher unit if the individual pieces of the unit are considered as separate process units. We identify the furnace-cyclone combination, the secondary-deentrainment section, the pitch cooling section, the heavy and light flashed distillate condensations, and, finally, the

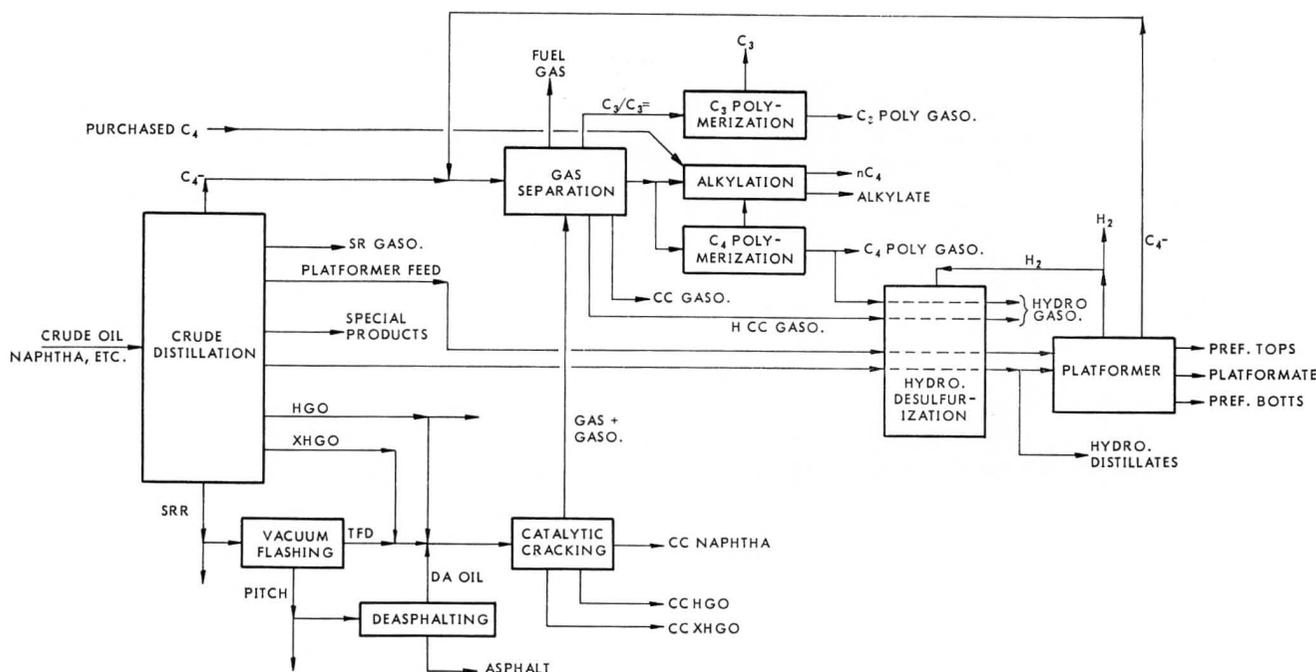


Figure 7. Typical Refinery Process Scheme. Blending of final products not shown.

steam ejector and gas system. Within each of these units or sub-units the same repetitive calculations exist. These can be separated into five steps: (1) the setup; (2) material balance; (3) heat balance; (4) constraint calculations; and (5) cost estimate and profitability.

Fig. 9 indicates how CHEOPS is structured to handle these consecutive calculations, using a set of individual unit sub-routines which describe the units in the actual process. CHEOPS will operate with any of a number of optimization algorithms, as long as they are structured in the form given in Eq. 1. By following a few simple

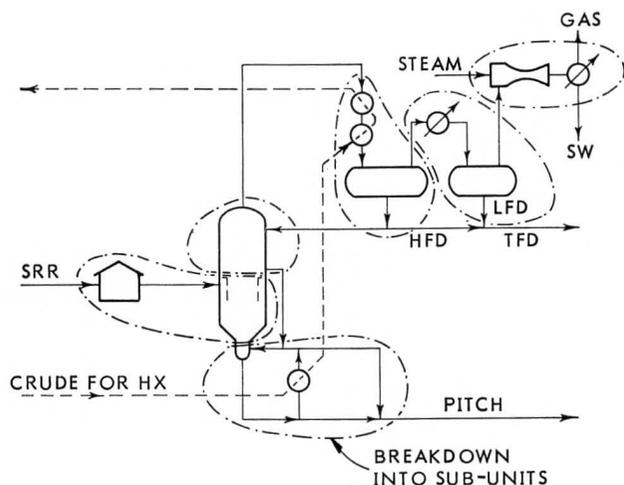


Figure 8.

rules, the sub-routines for each unit can be structured to supply the necessary answers to each part of CHEOPS. Further details on this appear in Table 1. This table and Figs. 7 - 9 are all taken from our earlier publication.¹⁸

LIMITATIONS ON PROBLEM SIZE

Precise formulation of the size of problems which can be conveniently or economically handled by optimization is very difficult. For one thing, such limitations depend greatly on the complexity of the simulation. If extremely detailed, complex solutions are desired, this will lead to extensive sub-programs just to describe the engineering. If such programs become too large, they will exceed the available core in the computer, which means that one must go to multi-coreloads, with all the attendant bookkeep-

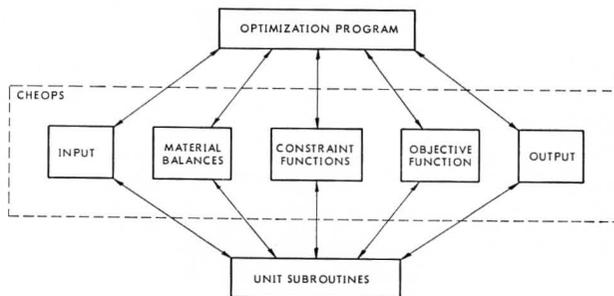


Figure 9.

Table 1. Program Functions for CHEOPS.

| Section | Optimization Program | CHEOPS Program | UNIT Subroutine |
|---------------------------|---|---|--|
| Initialization | Initializes optimization algorithm | <ol style="list-style-type: none"> Loads data, which may include: <ol style="list-style-type: none"> Control for optimization Control for material balancing Control for objective function calculation Control for output General economic and cost data Overhead cost parameters Offsite capital parameters Utility cost parameters Tankage parameters Prices for supplies and materials Plant feed amounts, prices, and properties Plant product amounts, prices, and properties Component properties Flow-diagram connections Optimization variable identification, bounds and starting values Constraint & equality identification and tolerances Parameters for UNIT subroutines Sets indices in UNIT subroutines Prints record of data and derived values Sets controls for remaining calculations | <ol style="list-style-type: none"> Calls INDEX subroutine of CHEOPS to permit setting indices Makes preliminary calculations independent of decision variables (except for a possible dependence on their starting values) |
| Material and heat balance | Sets new values of decision variables, and calls for preliminary calculations at a new point | <ol style="list-style-type: none"> Calls UNIT subroutines for preliminary calculations Calls UNIT subroutines, checks flows, characteristics, and properties of recycle streams, makes adjustments, and re-calls UNIT subroutines until model is material and heat balanced Calls UNIT subroutines for utility demands and other functions. (returns to #2 if utility balance calculation affects process streams.) | <ol style="list-style-type: none"> Makes preliminary calculations which depend on decision variables, but not on stream flows, characteristics, or properties Calculates flows, characteristics, and properties of "asked" streams (normally, the streams leaving the unit) Calculates utility demands and functions to be used in both constraint and objective calculations |
| Constraint functions | Sets index identifying constraint function to be calculated, and calls for constraint calculation | Identifies unit number for constraint, and calls appropriate UNIT subroutine | Calculates constraint function |
| Objective function | Calls for objective function calculation | <ol style="list-style-type: none"> Calls UNIT subroutines in order Calculates and totals unit operating and capital costs Calculates raw-material costs, and product credits, as needed Totals utility demands and use, and calculates utility capital and operating costs Calculates indicated objective function, including tankage, overhead, offsites, etc. | Calculates the following cost contributions: <ol style="list-style-type: none"> Supply and material use Supply and material inventory Operating labor Repair and maintenance costs Capital cost (with useful life, and tax depreciation life, when applicable) |
| Output | Calls for output, identified as non-feasible, intermediate feasible, optimal, or program error | Outputs results, as indicated by printout-control data, tallies, and objective function value. Types of output variable are: <ol style="list-style-type: none"> Variables and constraint and objective functions Process evaluation summary Capital cost breakdown Utility use, demand, and costs Materials and supplies summary Process stream material balance Process stream flows and properties Equipment details (UNIT subroutines are called first to calculate additional results if desired) UNIT printouts (obtained by calling UNIT subroutines) | <ol style="list-style-type: none"> If called for equipment print-out, calculates details not required for cost calculations but of interest at point selected If called for UNIT print-out, outputs results as programmed |

ing problems. Hopefully, this situation will be much improved by the third generation of computers, once the necessary systems are fully checked out. In the meantime, for the second generation computer (IBM 7094 and the like), we supply the general guidelines given in *Table 2*. These indicate the size of usable problems in

term of the number of variables and constraints which can be conveniently handled by the optimization algorithms indicated. It is assumed that the equations relating these functions and variables are of no more than ordinary complexity.

The algorithms considered are as follows:

- LP — Several standard linear programming systems

Table 2. Usable Problem Size for Optimization Algorithms.

| | LP | Map | GP | PPNL | DA |
|---------------------|-----------------|--------|-----|------|-----|
| Type of Objective F | L | NL | NL | NL | NL |
| Decision Variables | | | | | |
| Linear | 10 ⁴ | 500 | 100 | 600 | 40 |
| Non-Linear | - | 100 | - | 60 | |
| Bounds | } 2000 | } 1000 | 200 | 120 | 80 |
| Constraints | | | 200 | 2000 | 20* |
| Equations | | | | | - |

*No more than two active at any one time.

can handle a practically-unlimited number of decision variables, and over 2,000 rows; the latter can represent bounds on the variables, constraints on combinations of variables, or equalities involving one or more variables. Note that all functions have to be linear, although it is possible to do a reasonably good job of representing a few non-linear relationships by defining new variables and constraints.

- **MAP** — The technique described by Griffith and Stewart¹² has been used very satisfactorily for problems with about 500 linear variables and 100 non-linear ones. The number of rows which can be conveniently handled is somewhat less than in LP, because the necessary step-size limitations on the non-linear variables add additional rows. However, the allowance of non-linearity permits practically as good a representation of the system with the smaller MAP formulation as with the large LP version.

- **GP** — or **Gradient Projection**.²⁵ The usual form of this algorithm (available through SHARE) can only handle linear constraints or equalities, but will handle a non-linear objective function. Although the limitation on constraints and bounds is fairly small in the usual programs, there is nothing inherent in the algorithm which requires this; it merely represents a balance between available core on the IBM 7094, and the complexity allowed for the non-linear system.

- **PPNL** — the **non-linear version of Partition Programming** described by Ornea and Eldredge.²⁴ This can handle much larger systems and can handle up to 60 truly non-linear variables, each of which can have bounds. The approximate size for the total number of linear variables is 600 and the total number of rows in the linear system is about 2000. Normally this system is used where the linear problem can be partitioned still further into smaller sub-problems, each of which is handled individually (but automatically) during the optimization.

- **DA** — **Deflected Assent**²⁹ is typical of many hill-climbing methods. It is very limited as to number of variables. However, it can handle extremely non-linear or discontinuous objective functions, and can satisfactorily treat non-linear constraints, as long as no more than two are active at any one time. A further advantage of this system and of others similar to it is the extreme compactness of the program itself. Use of DA may permit a much larger simulation model without requiring multi-core use. On the other hand, if the problem becomes nearly linear at the optimum, Deflected Assent may behave very poorly.

Much more significant than the actual computation time . . . is the program development time.

Nothing is included in this table about integer or discrete variables, since most algorithms to handle such variables are still in the experimental stage. The only general method that is really foolproof as yet is that of combinatorially going through all possible cases. This is quite feasible, — once it is set up automatically on a computer, — as long as the total number of cases is not more than a few hundred. However, for each case, it may be necessary to do at least a brief optimization of the continuous variables.

TIME LIMITATIONS

Other limitations on the usable size of problems arise from the various time requirements. First, of course, is computation time; this is not really too serious as long as the above size limits are met. Moreover, if the problem is important enough, whatever its size, it is possible to run it, — at least in a stepwise fashion. With a standard method of computer center organization, however, it is usually best to stick to runs between a few minutes and a few hours in length. Much more significant than the actual computation time for optimization is the program development time. With CHEOPS, it is possible to develop a useful process model, — for example, a model for optimizing the design of a chemical plant requiring several million dollars of invested capital, — in a matter of 4 to 6 weeks. But a complex of several plants or an oil refinery might require months and months of effort on the part of several programmers, even if they are given easy access to the computer. Still another type of time limitation concerns the acquisition of necessary data, i.e., the values of the parameters. Even if the model is being developed entirely on the basis of past information, the acquisition, assembling, and proper checking might take nearly as much effort as the program development. Finally, the processing of these data for new optimization runs is, in itself, a major task. For routine use of optimization models in analyzing different cases, and different sets of premises, or in routing scheduling operations of multi-plant or multi-refinery systems, it is essential that an organization be set up with a full recognition of the data processing aspects.

UNCERTAINTY AND ITS EFFECTS

In the above discussion we have been implying that the entire problem is deterministic; that is, that we can make decisions, once and for all, based on certain premises which are completely fixed, and come up with a true optimum value which will always hold. In many engineering problems, this is a close approximation to the true situation. However, as we begin to get more and more involved with the marketing and business aspects, we often get into situations where uncertainties dominate the effect. These uncertainties can be classified into four general types:

1. **The Form of the Model.** Under this heading comes the question of identifying the proper kinetics, choosing the right equations to represent vapor-liquid equilibria, selecting the right correlations for sizing equipment, and so forth. The only real cure for this uncertainty is to get the best model builders you can. The implication is that building the model is an engineer's job, not a mathematician's. Model-builders must be people with engineering judgment and, preferably, with some physical feel for the system.

2. **Accuracy of Data.** Once the form of the equations has been settled, we must estimate or select numerical values for the various parameters in the system. Some of these may be relatively precise, but for others, there may be distribution curves of values (probability distributions) about the average values. Where such inaccuracies become significant, we must use simulation or stochastic programming, as described below.

3. **Forecasts of Future Conditions.** Nearly all useful problems involve future behavior of the weather, customers, competitors, and so forth. Mechanically, we can handle these forecasts with the same techniques with which we handle uncertainties in data. However, philosophically, they are different in type; we are assuming what the future looks like. In reality, factors that do not enter into our equations may come to bear before we actually get the desired results.

4. **Responsive Actions of Others** In some cases even the forecasts are inadequate. In a highly competitive situation, where we are dealing with one or two competitors, one or two major marketers for our supplies, or one or two major customers for our product, it is very dangerous to forecast future action. If our optimization is to be of any value, we would expect to do something new, i.e., something we have never done before. Except in very limited situations, it is impossible to forecast what the response of a major competitor, supplier, or customer is apt to be to this new action. For this reason, we have studied the use of game-theory in analyzing such problems,¹⁷ but with only limited success to date.

OTHER APPROACHES TO MATHEMATICAL MODELLING

Because these uncertainties dominate many problems, an alternative technique has developed,

called Monte-Carlo Modelling or Simulation. In reality, this merely handles uncertainties of types 2 and 3, which can be represented by replacing each uncertain parameter by a probability distribution for the parameter values. With these distributions as guides, we select enough random cases to produce a truly average value, or preferably, a distribution of values for the desired objective. Many references describe this procedure. The text of Naylor, et.al.,²³ is one of the newest general references, while that of Franks⁹ concentrates on chemical engineering problems.

Unfortunately, use of these techniques generally makes optimization unwieldy or even impossible. The usual procedure is to use case-studies, where a few important variables are set at two or three values. Fortunately, in many problems where this approach is essential, optimization is relatively unimportant, precise selection of optimum variable values is prevented by the uncertainties. This is certainly true of the "venture analysis" of Andersen¹ or the "risk analysis" of Hertz.¹⁶ However, other problems could profit by a combined approach, which has been termed stochastic programming.^{20, 21}

One pattern for this stochastic programming is sketched in Fig. 10. The basic simulation of Figs. 1 and 2 appears at the left in Fig. 10. However, the parameters

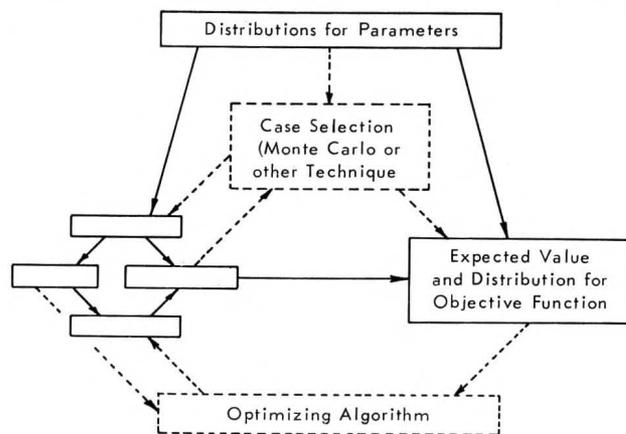


Figure 10.

are no longer fixed, but selected by some Monte-Carlo technique, from the given probability distributions. And the optimizing algorithm responds, not to individual values of the objective function, but to the expected value, or some other property of the calculated probability distribution for the objective function. Although many researchers are studying this and other formulations of stochastic programming, useful, general, computation systems are not available. Until they are, the engineer must select his tool according to the problem, optimization for deterministic, well-defined, many-decision problems, and stochastic simulation for highly-uncertain, few decision problems. (Continued on page 158.)

You won't just get your feet wet.

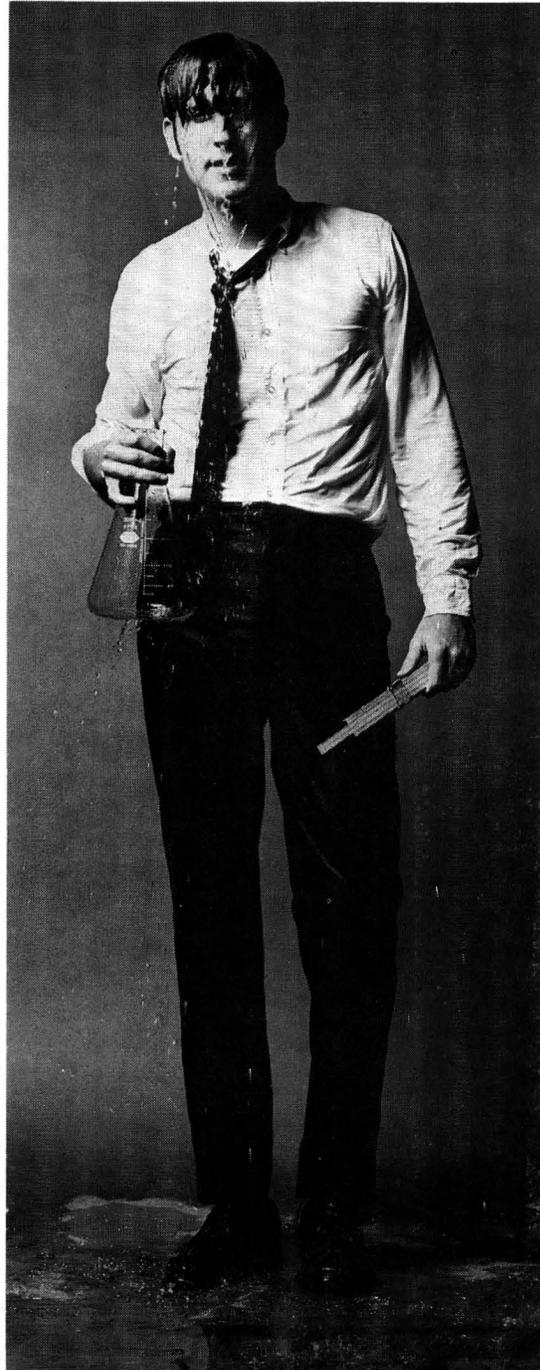
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ChE problems for teachers

1. Submitted by Professor R. B. Bird, University of Wisconsin.

Hydrostatic Pressure Distribution in Incompressible Fluids. Consider a beaker of liquid which, for all practical purposes, can be considered to be incompressible; let its density be ρ_0 . It is desired to obtain an expression for the pressure in the liquid as a function of position. Take the origin of coordinates to be at the liquid-air interface, with the positive z-axis pointing away from the liquid; let the pressure at the liquid-air interface be $p(0)$. A friend comes to you with the following comments:

- I. "By simplifying the equation of motion for an incompressible fluid at rest, I get $0 = -dp/dz - \rho_0 g$; I can solve this and get $p = p(0) - \rho_0 g z$. That seems reasonable — the pressure increases as one goes deeper and deeper into the liquid."
- II. "But, on the other hand, the equation of state of any fluid is $p = p(\rho, T)$. If the system is isothermal, then $p = p(\rho)$. If, furthermore, the fluid is incompressible $p = p(\rho_0) = \text{constant}$. This tells me that the pressure is constant throughout the field — which I don't believe!"

Clearly your friends need help. Explain.

2. Submitted by Professor Dave Chittenden, University of New Hampshire.

Computer Solution for the Adiabatic Flame Temperature. Find the adiabatic flame temperature for combustion of the following natural gas mixture: CH₄, 86.6%; C₂H₆, 7.9%; C₃H₈, 2.7%; C₄H₁₀, 1.3%; N₂, 1.5%. This dry gas is mixed with 130% theoretical air which contains 0.043 lb H₂O/lb dry air. The gas-air mixture enters the

burner at 500°K and 4 atmospheres pressure. Dissociation of water and carbon dioxide in the flue gases must be considered.

Solution:

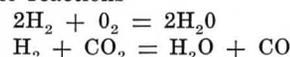
To do this type of computation, a general computer program in Fortran IV-G has been developed and tested on an IBM 360 Model 40 computer. To use the program, one keypunches a few IBM cards containing a description of the problem, and then the data cards are submitted along with a machine language program deck for processing.

The data needed for the calculation of the adiabatic flame temperature are as follows:

1. Number of hydrocarbon species in the gas mixture being burned.
2. Pressure in the burner.
3. Percent theoretical air (Must be equal to or greater than 100%).
4. Absolute humidity of the incoming air.
5. Number of moles of each hydrocarbon and of nitrogen in the fuel stream.
6. Heats of combustion at 291°K for all of hydrocarbon gases burned. (The heats to be used assume that gaseous water is formed in standard state reaction.)
7. Specific heats of all components in the range between 291°K and the flame temperature as a function of temperature.
8. Inlet reactant temperatures, which may be different for each reactant.

When the adiabatic flame temperature is calculated, a number of assumptions are made:

1. The process of combustion is adiabatic.
2. There is no secondary air. The hydrocarbons are completely converted using only the primary air.
3. The only combustion products are carbon dioxide, carbon monoxide, water, hydrogen, oxygen and nitrogen. These products are at the equilibrium conversions controlled by the equilibrium constants for the reactions



THEORETICAL FLAME TEMPERATURE (01A)

GENERAL CASE FOR NATURAL GAS MIXTURE

PRESSURE = 4.00 ATMOSPHERES
4 HYDROCARBON(S)

PERCENT THEORETICAL AIR = 130.00
0.04300LB H₂O PER LB DRY AIR

Input Data

THE DATA DESCRIBING THE REACTING HYDROCARBONS IS TABULATED BELOW

| FORMULA | HEAT OF COMB. | ENT MOLES | MOLES C | MOLES H ₂ | ENT TEMP |
|--------------------------------|---------------|-----------|---------|----------------------|----------|
| CH ₄ | -0.189700E 06 | 0.866 | 1.000 | 2.000 | 500.000 |
| C ₂ H ₆ | -0.336732E 06 | 0.079 | 2.000 | 3.000 | 500.000 |
| C ₃ H ₈ | -0.484100E 06 | 0.027 | 3.000 | 4.000 | 500.000 |
| C ₄ H ₁₀ | -0.630620E 06 | 0.013 | 4.000 | 5.000 | 500.000 |
| N ₂ | | 0.015 | | | |

Input Data

CAL/GMMOLE

DEGREES KELVIN

FORMULA OF HYDROCARBON OR EQUIVALENT HYDROCARBON
C 1.157 H 4.284

ENTERING MIXTURE BASED ON ONE MOLE ENTERING HYDROCARBON OR HYDROCARBON MIXTURE
MOLES OXYGEN 2.8964 MOLES NITROGEN 10.9109 MOLES WATER 1.0258

PERCENT COMBUSTIBLE GAS BY VOLUME = 6.32

GENERAL FORM OF THE SPECIFIC HEAT EQUATION
 $CP = A + B*T + C*(T)**2 + D*(T)**3$

CONSTANTS IN THE SPECIFIC HEAT EQUATIONS FOR THE REACTING HYDROCARBONS.
 CP UNITS ARE CAL/GMMOLES-DEG. KELVIN

| | A | B | C | D |
|-------|--------------|-------------|--------------|--------------|
| CH4 | 0.47500E 01 | 0.30000E-02 | 0.33630E-06 | -0.16450E-09 |
| C2H6 | 0.94400E 00 | 0.37350E-01 | -0.19930E-04 | 0.42200E-08 |
| C3H8 | -0.96600E 00 | 0.72790E-01 | -0.37750E-04 | 0.75800E-08 |
| C4H10 | 0.94500E 00 | 0.88730E-01 | -0.43800E-04 | 0.83600E-08 |

Input Data

THE DATA DESCRIBING ALL OTHER COMPOUNDS IS TABULATED BELOW

| | HEAT OF DISSOC. CAL/GMMOLE | ENT. TEMP KELVIN | A | B | C | D |
|-----|-------------------------------|---------------------|--------------|---------------|---------------|---------------|
| H2O | 0.57830E 05 | 500.00 | 0.832000E 01 | -0.653000E-03 | 0.270000E-05 | -0.614500E-09 |
| CO2 | 0.67960E 05 | 500.00 | 0.770000E 01 | 0.530000E-02 | -0.830000E-06 | 0.0 |
| H2 | 0.0 | 500.00 | 0.664000E 01 | 0.492000E-03 | 0.319000E-06 | -0.740000E-10 |
| O2 | 0.0 | 500.00 | 0.673000E 01 | 0.408000E-03 | 0.486000E-06 | -0.123400E-09 |
| N2 | 0.0 | 500.00 | 0.673000E 01 | 0.408000E-03 | 0.486000E-06 | -0.123400E-09 |
| CO | 0.0 | 500.00 | 0.673000E 01 | 0.408000E-03 | 0.486000E-06 | -0.123400E-09 |

TOTAL MOLES IN THE EQUILIBRIUM MIXTURE
 15.90913

FINAL MIXTURE COMPOSITION, MOLE PERCENT

| CO2 | H2O | CO | H2 | O2 | N2 |
|---------|----------|---------|---------|---------|----------|
| 7.22799 | 19.89369 | 0.04454 | 0.01823 | 4.23272 | 68.59292 |

PERCENT DISSOCIATION OF CARBON DIOXIDE = 0.61
 PERCENT DISSOCIATION OF WATER = 0.09

ACTUAL K = 0.264E 04 COMPOSITION K = 0.265E 04

THEORETICAL FLAME TEMPERATURE = 2016.619 DEGREES KELVIN

- The fuel contains only hydrocarbons and nitrogen. The air contains exactly 79 mole % N₂ and 21 mole % O₂.
- The properties of the reactant and of the product gases are calculated as mixtures of ideal gases.
- The flame temperature must be between 2500°K and 1900°K. This range includes the flame temperatures of all major hydrocarbons likely to be in a fuel gas.

The accuracy of the results obtained with this program is limited only by the validity of the above assumptions and the accuracy of the input data. The program user should try to insure that his specific heat data is

valid for the temperature range of the problem he is doing.

The results of computation for the above problem are shown in the figure. The input data read from cards is printed on the output as indicated. The other results are calculated by the program except for the specific heats of the output gases which are stored in the program.

Further information about the program can be obtained from Dr. David H. Chittenden, ChE Department, University of New Hampshire, Durham, New Hampshire 03824.

LETTERS (Continued from p. 109)

For the 40 graduate-inclined schools

$$P = 4.07 + 0.00B + 0.17M + 0.51D \quad (4)$$

and for the 57 undergraduate schools

$$P = 2.56 + 0.11B + 0.08M + 0.27D \quad (5)$$

One immediately notices that in Eq. 4 the coefficient of B is zero. This result may not be as outlandish as it appears at first blush. It indicates that in graduate-oriented programs the number of undergraduates may not appreciably affect the number of full-time professorial schedules. One may speculate that this is the result of a growing and perhaps regrettable practice of relegating undergraduate instruction to persons without professorial rank; i.e., instructors and graduate assistants. This practice may be dictated by necessity in rapid-growth situations.

If one compares the coefficients of D in Eqs. 4 and 5, one notices that graduate-inclined schools require more

professional time per doctoral degree granted than do undergraduate-inclined schools. The situation is reversed in the case of bachelor's degrees.

In conclusion, we wish to remind the reader that no great accuracy is claimed for this study. It represents a first attempt to analyze the relationship between the number of full-time professorial schedules and the number and kinds of degrees granted. Considering the nature of the variables, it is indeed surprising that the indicated degrees of correlation and stability exist. It would be interesting to follow the study with future ones, not only in chemical engineering but in other disciplines as well.

A. X. Schmidt
 Robert Pfeffer
 Leonard Cohen
 The City College of the City
 University of New York

THE DILEMMA OF INNOVATING SOCIETIES - FREDERICKSON

(Continued from page 125.)

internal factors. Clearly, as a society we are sensitive to and react to factors that arise outside of our geographical boundaries. The cold war, Vietnam, and the ABM are not strictly of our own doing. However, here we want to consider only those dynamics-determining factors that can be considered to be internal, since it seems that these are of greater significance than factors that can be definitely identified as external.

The first of these internal factors is the existence and propagation of what might be called the Creed of Technology. This is the widely held belief mentioned previously that innovation *per se* is good and that technology is always progressive. It might be argued that no intelligent, well-educated person really believes the Creed of Technology. If that is so, why do so many intelligent, well-educated persons *act* as if they did believe it? And if such is true of intelligent, well-educated persons, what beliefs are held by simple or uneducated persons in this regard?

By questioning the belief that innovation is always good, we are not thereby saying that it is always bad. The point is simply that if a technological innovation has a good side (as it almost always does), it will more than likely have a bad side as well. A case in point are those technological innovations that have led to large-scale agricultural use of fertilizers, herbicides, and insecticides. Surely these have greatly increased yields of crops and made possible a minimal standard of living for the world's expanding population. There is also no question that such use has led to progressive and cumulative deterioration and pollution of important sectors of our environment. Again, it is certain that these innovations have relieved the farmer of a number of burdensome chores, while on the other hand, it is possible to wonder if the farmer is any happier for being so relieved.

Associated with the Creed of Technology is the Cult of the Product. If the former teaches that innovation of itself is a positive good, the latter is the logical consequence of belief in that teaching. If innovation of itself is good, then the products of innovation — be they good or services — must themselves be good and those who deny this are either foolish or wholly mistaken. "For," claim the votaries of this cult, "our production of this thing or this service puts people

to work; it gives them useful labor in recompense for which they can obtain the good things of life. And our product itself satisfies a demand, otherwise we would hardly be making it. Therefore, it is patent on all counts that our product is a good thing, and deserves the importance that we attach to it."

Yes, but if your production pollutes the air that society must breathe or the water that it must drink, shall humanity at large share your enthusiasm for your cult idol? If this production necessitates tearing down and destroying the things of natural or man-made beauty that enrich life so much, shall the next generation of men hold you blameless? Where in the Cult of the Product is there any sense of *balance*?

A third factor, with roots perhaps deeper in human nature than any other, is the Gospel of Growth. This Good News is this: That the expansion of human activities (that is, the production and consumption of goods and services), institutions, and population is a wonderful thing, a panacea for economic and even social ills; without growth, society stagnates. With it, society's possibilities are unlimited. Hence, industrial or commercial enterprises are quick to brand themselves as "growth companies," chambers of commerce describe the community that they represent as a "vigorous, growing area," and radio and television advertising puts out an incessant barrage of propaganda designed to convince the public of the sovereign merits of industrial and economic growth. Placed before us are bright visions of a high-energy society, where man will control the weather or live under a weather-excluding dome, the grass will not have to be cut because it is artificial, the women will always be slender, young, and beautiful, and each of the kids can have a snowmobile for the winter, a sports car for fall and spring, and a speedboat for the summer. Or sometimes a different approach is taken; "If you don't grow you're dead!" is the hellfire-and-brimstone way to put it. And it is preached that way, apparently with complete conviction that it applied to human institutions and societies as it does to the biological cycle of growth, development, senescence, and death exhibited by individual living organisms. This sort of preaching has won converts, and it is difficult to escape the conclusion

. . . death and decay are necessary for birth and growth, and great Caesar's dust may appear in an ear of wheat as in a bughole stopper.

that for a substantial portion of the most influential elements of our society, growth has become an end in itself.

The biological aspect of the Gospel of Growth, viz., that population growth is an inherently good thing, is no longer a very explicit part of the Gospel's teaching. The social stresses and political and other problems brought about by overpopulation are so evident in so many parts of the world that it is no longer fashionable or expedient to come right out and urge population growth. However, the teaching that population growth is inherently good is implicit in the Gospel of Growth. For if expansion of the production of goods and services is a good thing, then population growth must also be welcome, for besides increasing per capita consumption, what other way is there of increasing total consumption, the *sine qua non* for increasing production?

IF, AS SUGGESTED ABOVE, THE HELL-fire-and-brimstone aspect of the Gospel of Growth is based on the invalid analogy that the development of a society follows the same rules as the development of individual living organisms, it is nevertheless permissible and even necessary to view the development of societies in biological terms; not in the sense of trying to draw analogies, since these are always of doubtful validity, but in the sense of trying to see what restrictions biology places on such development. For instance, American society is composed of a biological population inhabiting a large but strictly bounded living space. Very many other biological populations, ranging from bacteria to beef cattle, share this living space with us. All of these populations — man's included — are subject to biological, chemical, and physical laws that cannot be suspended or amended by majority votes of our legislatures. In that sense, man can never "master" nature. In many cases, these laws are not all known with precision or else their application is too complicated for quantitative prediction; in such cases, it is not possible to predict what consequences human actions will have on our environment. It is necessary to mention this here, since the contrary belief — that we can predict everything — is quite common in our society, and is the essence of what we shall call Technological Megalomania (see below).

Moreover, even if population growth is not an explicit teaching of the Gospel of Growth, the current policies

of our society guarantee that the population will continue to grow anyway. The demographer Judith Blake has recently pointed out* that Americans of all classes consider it desirable to have large (greater than two children) families: the mean number of children considered desirable varies from 3.2 for high-income and college-educated women to 3.6 or 3.7 for low-income or grade-school-educated women. If that is what is considered desirable, then that is what couples will strive to attain, and so in fact the natality rate is much greater than that required to achieve a stable population.

Professor Blake attributes the desire for large families to "pronatalist policies" of our society, policies which evolved primarily in response to the past need for a high natality rate to counteract the then-prevailing high mortality rate. She says (pp. 528 and 529) that these policies "insure that just about everyone will be propelled into reproductive unions, and [the female] half of the population will enter such unions as a 'career' — a life's work. This rigid structuring of the wife-mother position builds into the entire motivational pattern of women's lives a tendency to want at least a moderate-size family. . . . the wish for a family of a particular size . . . relates . . . to a need for more than one or two children if one is going to enjoy 'family life' over a significant portion of one's lifetime."

However, the predictions based on these laws are quite clear even if not specific when they are applied to a population that is growing unchecked by any competing population, by disease, by intraspecific rivalries, or by lack of food: eventually one or more of these factors will exert themselves and bring about a check to population growth. It is true that by very great expenditure of effort — an expenditure that we do not now seem willing to make — the density of population at which such limiting factors come into play can be raised. But how high can it be raised? That is one of the things that cannot be answered with precision. Concerning this, the ecologist Lawrence Slobodkin writes* (pp. 3-4): "How many men can the earth hold? We must abandon all pretense of saving intact any wilderness areas and consider that we will treat the earth as a combined garden and factory; all other species will either prove useful to man or will be eliminated; they will either adjust to the omnipresence of man or die. Answers to the question are now merely guesses, ranging from 7 billion to 200 billion, the difference in the estimates depending on how several subsidiary questions are answered." And what would it be

* Judith Blake, "Population policy for Americans: Is the government being misled?" *Science*, 164, 522-529 (1969).

* Lawrence B. Slobodkin, "Growth and Regulation of Animal Populations," (New York: Holt, Rinehart, and Winston, 1961).

like to live in such a world? Again we quote Slobodkin (p. 4): "Implicit in this picture of the future is a mental health problem: a world completely full of man and his activities could well be a maddening place. There is an esthetic problem: the beauty of the wilderness is a very real thing. There is a political problem: a world full of men would be highly regimented, a world of an Aldous Huxley or Orwell phantasy." When measured against this sober (and understated) appraisal, the Gospel of Growth begins to lose some of its appeal. And what about that aspect of the Gospel calling for continual expansion of man's activities and man's consumption, and not just total expansion, either, but expansion per person? This compounds the problems raised by the population explosion and hastens the time when some limiting factor beyond man's control will appear.

If our (U.S.) population were stationary, and if our per capita rate of consumption of goods and services were stationary, both at their present levels, then we could probably afford to indulge ourselves in the other follies enumerated here. It seems perfectly reasonable to assume that with existing technology, or with technology within the reach of present knowledge, we could provide the necessities of life and many luxuries in addition, as well as a clean, esthetically-pleasing environment, for all of the 200,000,000 people who now live in the United States. But of course, our population and our per capita consumption are not stationary, and these are facts of cardinal importance.

The Gospel of Growth is at once the most insidious and the most dangerous of all the internal factors that will be considered here. It is the most insidious because its biological aspect is based on an eminently reasonable postulate: that we must reproduce ourselves if human life is to continue on the earth. It is the most dangerous because it interacts with and is reinforced by all the other factors that we are enumerating, and because by itself, it is a sufficient condition for producing ecological catastrophe. We need to take a long look at the Gospel of Growth.

STILL ANOTHER INTERNAL FACTOR that determines the dynamics of our society is that which gives rise to what my biomedical librarian friend calls the Sandbox Syndrome. She coined this term one day when we were trying to get to downtown Minneapolis. That day it seemed that our path was diverted at every intersection by a huge hole dug in the earth for a freeway, by some enormous piece of earth-moving machinery blocking the street, or for preparations to throw up a new skyscraper. After the tenth detour, she exclaimed "Why, this is the Sandbox Syndrome; dig, dig, dig all the time!"

. . . the sandbox syndrome; dig, dig, dig . . .

In case there be any uncertainty about it, let us place in more explicit if less expressive terms that which Miss Bohn so aptly characterized: We shall say that an individual, an organization, or a society exhibits the Sandbox Syndrome if his or its thinking tends to be determined by technological considerations, if it is fixed upon the size or the speed of machines or projects, or if it habitually turns to digging in the dirt, rearranging the landscape, and generally "improving upon nature."

A case that was a classic example of the Sandbox Syndrome appeared on TV a few weeks ago. An official of one of the large airline companies was describing the SST. Facts and figures concerning the weight, size, thrust, speed, carrying capacity, length of runway necessary for takeoff, etc., came spewing out of him as paper comes spewing out of the University's CDC 6600 computer. But never a word about sonic boom, release of pollution high in the atmosphere where dispersal is very slow, or the consideration that it may not be necessary or even desirable to be able to fly from Minneapolis-St. Paul to London in four hours. The whole thing was reminiscent of a joke once told by a colleague: The passengers on the first commercial flight of the SST had fastened their seat belts in preparation for blast-off and the doors had been sealed. A voice came over the PA system and announced that "This is a recording. The doors of the craft have been sealed and the program for takeoff initiated. In two hours we shall touch down in London. This operation is completely computerized and is not subject to human error. So relax, enjoy the flight, and be assured that nothing can go wrong nothing can go wrong nothing can go wrong. . . ."

The forms of the Sandbox Syndrome described above are of a relatively primitive nature. More advanced forms are sometimes manifested and these should perhaps be differentiated from the Sandbox Syndrome; we might call these Technological Megalomania. Particularly striking here is a tendency to view the earth as some sort of spacecraft, with the earth's human population as its crew and all the rest of the earth's populations as its life support system. The mission in which this super space vehicle is engaged is tremendously exciting, if rather ill-defined. Hence, we must manage the life support system and harness it — every organism of it — to the one task of supporting the crew. And of course all of the crew must dedicate themselves to the great task of completing the mission. Possibly the crew might become somewhat restive in their cramped quarters (even though these be scientifically designed), but no doubt application of psychology, genetic strain selection, and new in-

It is absolutely necessary . . . that innovating societies think about why they innovate and what the consequences of innovation are.

novations in crowd control will minimize any disturbances.

Another striking manifestation of Technological Megalomania is a willingness to play the Game of Environmental Russian Roulette. The elements of this Game are first a technological innovation magnificent in conception and grandiose in scope, second a considerable uncertainty about the long-term environmental consequences of implementing this conception but a possibility that these consequences could be serious indeed, and third a willingness to proceed with implementation anyway.

A STRANGE OPHTHALMIC DEFECT THAT we can call Utilitarian Vision is still another factor that directs technological innovation into dangerous channels. Characteristic symptoms of this defect are: Looking at a forest and seeing piles of boards instead of trees, looking at an old but well-kept neighborhood and seeing high-rise apartment buildings instead of homes, and looking at an unspoiled river valley and seeking a power plant with a six hundred foot smokestack instead of a place where future generations of men can breathe and renew their spirit. Sometimes, the defect becomes so severe that the boards, apartment buildings, and power plant of the foregoing examples are distorted further into dollars. When that symptom shows up, there is little that anyone can do to correct the defect. And please do not assume that because Utilitarian Vision has been illustrated by homely examples that strike most closely at the author's heart that it does not operate on a much larger scale.

Another internal factor of importance is the Concept of the Convenient Society. If some of the other factors that have been enumerated arose far back in the past or are inherent aspects of human behavior, the Concept of the Convenient Society is of recent origin. Indeed, to gauge by the drumfire of advertising in its behalf, we can probably infer that the principal financial beneficiaries of the Concept are not perfectly sure that it has taken complete root in the thought patterns of the American people.

What is the Concept of the Convenient Society? Simply this: That everyone ought to have all of the conveniences that our technological capacity can produce, and that that capacity ought to apply its ingenuity to the fullest to make things ever more convenient. And part of convenience of course is easy of disposal when an object is empty or worn out; we cannot worry about what becomes of our conveniences when we are through with them.

The basic trouble with the Concept of the Convenient Society is not that convenience is immoral or that we should go back to the "good old days." Rather, it is the fact that the Concept is totally at variance with the ecological concept that in a limited, living world, all material things must cycle if life is to continue indefinitely. To put it in a different form, death and decay are necessary for birth and growth, and great Caesar's dust may appear in an ear of wheat as in a bung-hole stopper. The Concept of the Convenient Society either does not recognize the necessity for the recycling of materials or if it does, it ignores the necessity. Thus, a shiny new car eventually ends up a rusty wreck and so our endless production of automobiles and concomitant failure to reuse the worn-out ones leads to the proliferation of auto junkyards. Again, a new house in the suburbs becomes an old house in a slum — you can see this happening already and few of our suburbs are more than twenty-five years old — so the better-educated, more affluent people move on to a new suburb and start a new cycle of development and decay; thus, the urban blight spreads over the land. Perhaps the whole thing can be epitomized by the Story of the Aluminum Beer Can. It started out in the mind of some ingenious innovator. Industry fashioned it into a shiny vision of promise. Its production, filling, and distribution provided useful work for more than one deserving man. It gave pleasure with convenience to someone else. And then it ended up with glass bottles, plastic-coated milk cartons, throw-away aerosol cans, aluminum trays from TV dinners, and an endless variety of other junk in an ever-growing and unholy mountain that does not rust or rot, and whose eventual disposition is or ought to be giving gray hairs to the city fathers.

THIS ESSAY WOULD BE UNBALANCED UNLESS we conclude the catalog of the foibles of our innovating society with mention of the general ignorance of, or indifference to, the full costs of technological innova-

tion. Everyone wants the necessities of life, and everyone also wants a greater or lesser share of the amenities of life. Unfortunately, production of both necessities and luxuries entails charges against the environment. It is even more unfortunate that society at large has only a dim awareness of the nature of these charges (or even that they exist;) and blithely dismisses the thought of charges with the assumption that they are not serious or will somehow be paid by some unit of government or industry. Of course, the charges sometimes become blatantly obvious, as in the recent oil-drilling catastrophe on the coast of California, and the public ire is then aroused. This wrath tends to center on the offending company or on the government official who permitted the risk to be taken, and that is indeed proper. However, fairness demands the remark that the public's own hands are not entirely clean in this matter; after all, if no one drove a car, would it be profitable to drill for oil off the shore of California?

The trouble here is that no one has told society at large what the environmental costs of the innovating society are. The dissemination of such information is desperately needed, for unless it is available, one cannot see how a rational set of priorities designed to balance man's needs against environmental costs can be enforced. Hence, five minutes of gibes at air pollution by Arthur Godfrey are no doubt worth one thousand essays like this, but the author is compelled to write it nonetheless.

The set of factors that have been described give to the dynamics of American Society something of the character of a branching chain reaction. The creed of Technology and the Gospel of Growth serve as the initiating reaction. Once technology is initiated, it is propagated by the Cult of the Product and the Concept of the Convenient Society. The Gospel of Growth gives rise to branching reactions at all stages of the process. And those defects in our thinking that manifest themselves as the Sandbox Syndrome, Technological Megalomania, Utilitarian Vision and ignorance of the costs of the innovating society, make it virtually impossible to introduce any terminating reactions into the whole scheme.

We have now reached the point where we can see that some terminating reactions are needed if we are not to strangle ourselves. The air and the water have become so badly polluted that the situation is apparent to everyone. Hence, individuals, organizations, and industries of vision and conscience have become concerned about pollution control and the effects of pollution on our environment and what is even more important, are acting on their concern. Thank God for such; we are indebted to them. Nevertheless,

the efforts we have today are not nearly enough, nor in the long run, do they strike at the heart of the matter. Unless America changes some of its basic attitudes — the internal factors mentioned above — it is hard to see how even very great efforts to control pollution can be much different from a rear-guard action. Hopefully, they can keep us one jump ahead of the wolf for some time, but what is really needed is some way to chain the wolf and put him to work for us.

It is absolutely necessary for the continued existence of a descent sort of human life on this earth, that innovating societies think about why they innovate and what the consequences of innovation are. We must recognize that innovations are a means to an end and not the end itself. We must try to set up some definite goals that have the benefit of all mankind as their objective. We can no longer rely on a vague faith in progress to take care of our tomorrows. Only by setting up defined goals will it be possible to develop priorities and institutions that can guide the innovative genius of men onto paths that will be truly, as opposed to superficially, beneficial.

I DO NOT THINK THAT WE ENGINEERING educators have done very much that is useful with regard to the considerations raised above. True, we need and shall continue to need engineers and scientists, and it is our business to produce them. But what *kind* of engineers are we turning out? It seems to me that much of current engineering education serves to reinforce belief in the Creed of Technology and the Gospel of Growth, and all the rest of those factors, factors with which the freshman engineering student has already been partially equipped by his parents, his schoolmates, and society in general.

Readers who have persevered this far and who agree that I have described some real problems will probably wonder if I have any concrete suggestions to offer for their solution or is it to be simply "*écrasez l'infame*," an attitude all too common these days. It seems to me that there are some things we can do, and even if they are not very original, I give them for what they are worth.

The most immediate thing that we can do is to consider the contents of our undergraduate textbooks and courses. It is true that these do not exhort budding engineers to go out and rape the environment. But it is also true that they do not suggest that they have any responsibility to conserve it nor do they often state that technology imposes any stress on the environment. To be aware that a problem exists is the prerequisite for any attempt to solve the problem, and by judi-

. . . the mystic destiny towards which innovating societies strive has lost some of the rosy tints of paradise and taken on the more lurid aspects of purgatory.

cious choice of examples in engineering texts and courses we could certainly point out to our students what some of our real environmental problems are. Such examples serve another purpose also: they can be genuine and challenging illustrations of basic engineering principles, ranging from applications of the laws of thermodynamics to problems of diffusion and convection that are as advanced as anything in Birdfoot. Why don't we try to put this sort of example into our texts and courses? We don't have to expurgate as Mother Goose must be expurgated; we merely need to *add* things.

Another useful thing that we can do is to make an attempt to recruit women students for engineering. This would help to open up careers for women other than or in addition to that of wife and mother; it would be a removal of one of the factors repressing antinatalist tendencies existing but not active in our society. Removal of factors repressing antinatalist tendencies is Judith Blake's principal suggestion for inhibiting population growth in the United States. By acting on her suggestion, we would also tap a source of talent and brainpower that has hardly been touched by engineering.

The next thing that we can do is to see that our students are at least exposed to courses in environmental engineering. Does our school have courses in air and water pollution control? Do we encourage our students to take these courses? If we do not have such courses, what are we doing to get them?

Finally, it is clear that an innovating society will be able to resolve its basic dilemma only if it can replace those attitudes and values that we have named as the Creed of Technology, the Gospel of Growth, etc., by attitudes and values more in keeping with the long-term needs of man. It is equally clear, at least to the author, that if this is to be done at all, it must be done through education. Hence, what about our own attitudes? In our teaching of the details of technology, do we ever stop to point out that technology is a two-edged sword? Indeed, do all of us even believe *that*? Do we think it worthwhile for our students to learn something besides science and engineering or do we regard the "liberal education" part of our curriculum as a necessary evil forced upon us by the rest of the university? Do

we have any concern that our students should realize that we live in a limited world, a microcosm, whose living and non-living components interact in an endless spectrum of ways, some of them of extraordinary subtlety? Do we think students should be aware that man is part of this microcosm or are we so far gone into the last stages of Technological Megalomania that we teach or at least imply that he is above and beyond it? Have we swallowed the Concept of the Convenient Society — which is in essence that we can do just as we damn well please with our surroundings — so that we pass this monstrosity on to the next generation of engineers?

We are concerned these days with a decline in the number, or at least of the relative number, of students entering college who want to become engineers or scientists. Surely there is no single or simple explanation for this, but I do think that we can gain partial insight into the phenomenon by applying the analysis given above. Eighteen year olds can observe and draw conclusions as we can. Their observations may not be as thorough, and their conclusions may not be based on a very disciplined or experienced thought process; nevertheless, the Creed of Technology, the Cult of the Product, and all the rest are fairly obvious aspects of our society, and it is easy to see how they could become inextricably entangled in the minds of youth with science and engineering. The fact that these factors are faults of society as a whole rather than of technology alone is irrelevant; society's defects are manifested in a most striking way by our runaway technology.

To close this essay, let us return to Professor Pig-gott's opening chapter. He speaks (p. 18) of a "mystic destiny" towards which innovating societies believe they should strive by continual technological innovation, and his quote from Herbert Spencer may be taken as the canonical form of the Creed of Technology: "Progress is not an accident but a necessity. It is a part of nature. Evil tends perpetually to disappear." Unfortunately, the stock of evil seems these days to increase even faster than the population. Change is a part of nature but that which is called Progress is often a retrogression, or if it is of benefit to us, it would be a curse to the next generation. Thus, the mystic destiny towards which innovating societies strive has lost some of the rosy tints of paradise and taken on the more lurid aspects of purgatory.

I am indebted to Carol Urness for her constructive criticism of my original manuscript.



THE GATORS GO

RAY FAHIEN

What should be the goals of a department of chemical engineering? National prominence through a strong graduate program or a quality undergraduate program? An orientation toward "engineering science" or an orientation toward engineering practice? A large graduate program or a large undergraduate degree production? A PhD-oriented graduate program or a master's-oriented graduate program? Should it espouse a philosophy of service to the state, a philosophy of service to the engineering profession, or to a "community of scholars"?

When a department has a single objective, the fulfillment of its goal demands a concentrated effort in one direction. For example, a department that is interested in undergraduate degree production can hire faculty who are inspiring teachers and who would also enjoy visiting high schools to aid in recruitment; a department that aspires to national prominence for the quality of its research can hire faculty who have brilliant, creative minds and a personal desire to do research and to publish their results. When the goal of the department is singular, and when the faculty and administration accepts the singularity, the implementation of its goal can be carried out smoothly and without conflict. Departments of great prominence can be developed in this manner.

. . . a balanced department with multiple objectives is desirable at the University of Florida . . .

In many cases, external factors, such as whether it is a private or public institution, may influence or even fix the goal of the department. In some cases, it is more desirable (and even necessary) for a department to have multiple goals. For example, the composition of a tenured faculty can, by its very nature, demand a diversity of objectives; or the faculty may express an objective opposed to that of the institution or college as a whole (such as in the case of an undergraduate-oriented faculty in a graduate-oriented institution).

While many departments seek more than one of the many objectives listed above, few of them strive for excellence in **all of them**. But one department that, for the last four or five years, has been attempting to do all of these is the Chemical Engineering Department at the University of Florida. We might therefore properly ask the following questions:

What are the reasons for such a multiplicity of objectives?

What kind of results have been achieved?

JUSTIFICATION FOR BALANCE

A balanced department with multiple objectives is desirable at the University of Florida because of the following:

- It is the *only* department of chemical engineering in a state serving over six million people; it therefore feels a broad responsibility to provide a diversified and balanced program.

a department must recognize both academic and industrial professional goals . . . its achievements will never be easily measured by quantitative indices . . . an engineer is not merely a technical robot . . . the goal of the department, and that of the student it educates, must be the betterment of human society.

- Its tenured faculty in 1964 was already of above-average size; it was a diversified, heterogeneous and capable group that was brought together to do sponsored research under the Engineering and Industrial Experiment Station and partly to teach. It consisted of several people with degrees in chemistry (organic, biochemistry, pharmaceutical, inorganic and physical), a pulp and paper technologist, an authority on imbedding flowers in plastics, an expert on asphalt technology and economics, a world-famous fluorine chemist (and philosopher of science and education), and an electrochemist doing over \$100,000 a year of research (much of it classified) on thermal batteries and fuel cells. Some of the faculty were interested only in undergraduate teaching, others only in sponsored research, still others in both activities. Its average age was 55 and there was only one assistant professor in the group.

- The new energetic and dynamic dean of the College of Engineering from 1964-68 strongly encouraged the development of the graduate program — both from the standpoint of increased enrollment, and also in terms of quality of research and instruction.

- It began participation in 1965 in an NSF Science Development (or "Center-of-Excellence") Grant that provided funds for bringing in new faculty and graduate students to do fundamental research in chemical engineering.

The diversity of faculty interests and backgrounds plus the strong leadership of the dean made it obligatory for the department to pursue multiple objectives — lest it suffer from internal conflict among its faculty or from an external gap between the objectives of the administration and those of the faculty. Hence the objectives of the department became balanced ones and diversified ones; *both* quality *and* quantity were needed in the graduate *and* undergraduate program; *both* theory *and* practice had to be emphasized; *both* teaching *and* research had to be acknowledged; both masters *and* PhD degrees had to be offered; and *both* service to the State and Nation as well as service to the engineering profession and to the academic community had to be a part of departmental philosophy.

To express these multiple goals in a cohesive philosophy became a first task of the new chairman when he arrived in June 1964. A statement of goals recognized the diversity of the chemical engineering profession through its strong roots in both chemistry and physics. This diversity meant that a chemical engineering department must recognize bifold professional goals: *academic* goals that strive for the advancement of fundamental knowledge and *industrial* (or pro-

fessional) goals that have to do with the economical design and operation of plants that produce consumer goods (or of substances that go into making consumer products). "*Just as the overall aim of the University is to serve mankind,*" it further stated, "*so also the goal of the department, and that of the student it educates, must be the betterment of human society. For as a professional man, an engineer is not merely a technical robot who responds passively and unquestioningly to conformist pressures or to the commands of others.* Instead he must be aware of, and deeply concerned with the social and political problems of our times. He must have a high sense of values and be capable of making decisions with regard to principles and ideals derived from these, rather than from narrow self-interest or partisan group interest. In keeping with this philosophy, the department should investigate methods of establishing communications between the 'two cultures' of technology and the humanities."

Somewhat later the first annual report for the "Center of Excellence" Grant stated that "the goal of the chemical engineering department in the Science Development Program is to strive towards an excellence that is better expressed in terms of the significance of its contributions to scientific progress than by the volume of its activity. *Its achievements therefore will never be easily measured by quantitative indices—by numbers of students or faculty added, by the dollars worth of equipment purchased, by the number of papers in various journals, or by the number of degrees granted. We believe that the kind of excellence for which we strive cannot readily be programmed, budgeted or allocated on a yearly or semiannual basis. Nor can it be fully accomplished in a time space of one year or three years or even five years.*

"But seeds can be planted. Morale can be improved. Research ideas can be generated. New approaches to engineering education can be tried. A creative intellectual atmosphere can be developed. Bright, highly motivated people, both young and old, can be added to a faculty. A new life, energy, and enthusiasm can be breathed into a faculty with unfulfilled goals and unrealized potential.

GRADUATE ENROLLMENT TRIPLES

With the addition of a new chairman and three other faculty members, the chemical engineering department began its period of development in 1964-65 — one year prior to the award of the "Center of Excellence" grant. Although this development was greatly accelerated by the award of the grant, it was partially retarded by inadequate space and facilities. Until November, 1967, the department had been housed entirely in a crowded World War II airplane hangar which was shared with the Aerospace Engineering Department. Essentially no additional space was available for graduate students and research equipment, and faculty offices were not conducive to the recruitment of prominent senior faculty members. But in less than three years the department could point to the following accomplishments:

- Revision of graduate and undergraduate curricula.
- Graduate enrollment nearly tripled increasing to 66.
- Undergraduate degree production increased 50%.
- Seven outstanding young faculty members with excellent backgrounds were added, decreasing the average age of the faculty from 55 to 44.
- Sponsored research support increased over 50%.
- Faculty research productivity in terms of papers submitted and published increased several fold. Two books were published and two others were started.

Although the above quantitative increases may be startling, even more impressive were the indications of improvements in the *quality* of its graduate student body, its faculty, and its graduate program. In 1964, over half the 23 graduate students were foreign students, and roughly half were University of Florida graduates. The average Graduate Record Examination scores of that group was 550 or slightly above average. However of the group of 28 students admitted in Fall, 1967, all but two were graduates of American institutions other than the University of Florida. The first group of 22 who accepted appointments had an average Graduate Record Examination (Verbal-Quantitative Average) score of 654 — at least one standard deviation higher than in 1964. (Such a score meant that the *average* student was in the top 6-7% of the senior students throughout the nation who took the examination.)

Initially, the award of the "Center of Excellence" grant made possible a shift in the research emphasis of many of the older faculty members

to more fundamental areas of research and away from the highly applied sponsored research projects previously emphasized under the Engineering and Industrial Experiment Station. As a result of this heightened interest, new proposals for fundamental research were written and nine new projects were accepted for support by various agencies such as the NSF, NIH, AEC, NASA and DOD. Thus stimulated, the face value of sponsored research nearly doubled and the annual rate increased by over 50%.

The increase in outside research support made available state funds for the addition of new faculty beyond the two positions allocated in the grant. (In addition to positions generated through research, one state supported position was obtained from the University.) The new faculty added were not only graduates of leading institutions; they were also generally among the top students to complete PhD work at their institution over a period of years. (Four of them had won NSF Fellowships in national competition.) Table 1 gives their backgrounds.

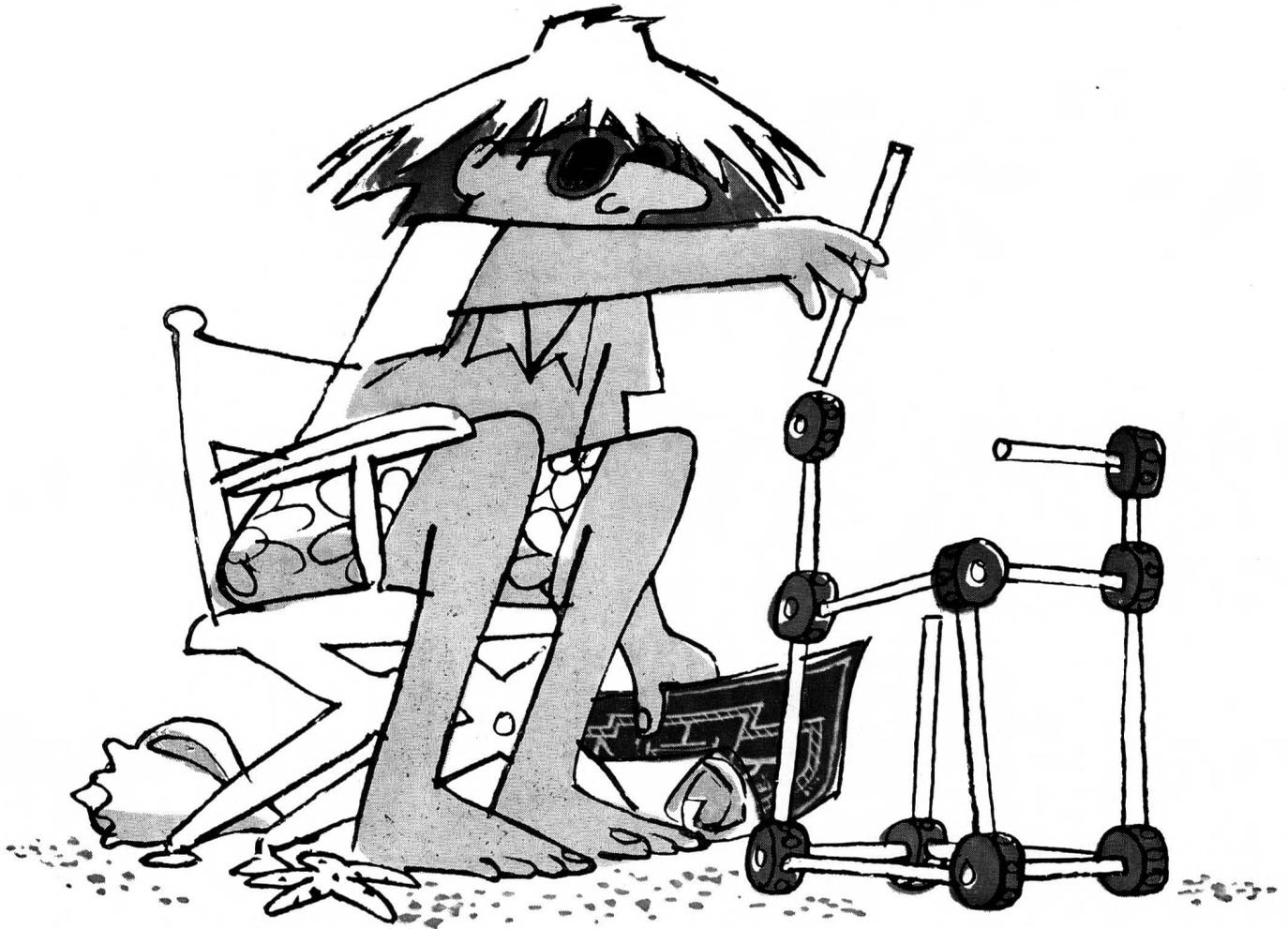
TABLE 1. FACULTY ADDITIONS SINCE 1964*

| Name and Ph.D. School | Area | Other Background |
|---|---|---|
| A. W. Westerberg London | Computer-Aided Design | Control Data Cp. Princeton U. U. of Minnesota |
| L. E. Johns, Jr. Carnegie Tech | Polymer Dynamics Cont. Mech. | Dow Chemical |
| J. P. O'Connell Cal. Berkeley | Thermodynamics Transport Properties | Mass. Inst. Tech. Pomona Coll. Union Oil Co. |
| X. B. Reed, Jr. Minnesota | Bioengineering Appl. Math | U.C.L.A. Texas A & M |
| A. D. Randolph Iowa State (Now at U. Arizona) | Crystallization- Particulate Systems | Amer. Potash Spencer Chem. Co. Colorado U. |
| D. W. Kirmse Iowa State | Turbulence | Union Carbide Oklahoma State |
| K. E. Gubbins London | Transport Properties | Florida U. (Post Doc) |
| R. W. Fahien Purdue | Transport Processes in Reactors | Ethyl Corp. Iowa State U. Missouri (Rolla) Washington Univ. |

*Ronald Gordon (Ph.D. expected from Princeton University) will join faculty in September 1969.

(Continued on page 157)

would you like to plan a plant in Puerto Rico?



Too late, the plant is planned! In fact construction is already beginning on Sun Oil's new \$125 million refinery complex and harbor at Yabucoa.

But the project at Yabucoa is simply one indication of Sun on the move. We're geared for growth and we need people. Maybe you?

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FLEXIBLE CURRICULA CAN BE STRONG

RAY FAHIEN
MACK TYNER
R. A. KEPPEL

*University of Florida
Gainesville, Florida*

UNDERGRADUATE PROGRAM IS DIVERSIFIED

There is much truth in the old story about the late G. G. Brown telling a questioner that "chemical engineering is what chemical engineers do." When asked what chemical engineers do, his reply was, naturally, that they do chemical engineering! But, contrary to the belief of certain narrow-minded persons, there is no single well-defined job that each and every chemical engineer does and which can be described as THE work of "THE chemical engineer." For in practice individual chemical engineers do numerous kinds of jobs each requiring different talents, abilities, and interests.

In spite of this great diversity of the profession, chemical engineering curricula have for years consisted of a rigid set of courses that every student was required to take. No consideration was made of his future career objectives, his personal interests, or his individual abilities. Although the typical curriculum might include perhaps two elective courses, these were often gleefully squandered in subjects such as bait casting, photography, or basket weaving. In view of our special nature as the only chemical engineering department in the State of Florida, we felt that we have special obligations to provide as broad a program as possible. *Accordingly, in 1965 we developed a curriculum that treated each student as an individual—one whose individual interests, talents, and career objectives could be expressed through a selection of option programs.*

The considerations that were involved in developing this curriculum are as follows:

First, we reaffirmed the belief that an engineering curriculum must be designed to prepare not only a broadly educated person but also train a professional man who could, upon graduation, do the kind of engineering work

that employers have associated with chemical engineering. Both of these educational objectives had to be fulfilled in four years since a five-year program has never been accepted by students, educators, or industry. However, it seemed neither possible nor desirable to devise a *single* four-year program that would prepare the student for *all* the various kinds of work that chemical engineers do. For it seemed wrong to subject the practice-oriented student to intensive theory and mathematics that he would not use; and it seemed equally unproductive of human talent to deprive the science-oriented student of that kind of experience that would best prepare him for graduate school and a career in research.

Second, we felt that it is essential that all programs in a chemical engineering department include those fundamental and core courses required for the practice of chemical engineering and that no program should be "watered down" so as to become an easy path to a cheap degree.

Third, we considered it important that a student not be unduly harmed by a wrong decision as to the program he chooses to enter. Therefore we made the differences between programs only about 10%. Actually since we require 213 quarter hours (142 semester hours) for a bachelor's degree, more leeway was possible than in schools requiring much fewer hours.

Fourth, we felt that a student should not be forced to make a decision until his senior year so that he is experienced and mature enough to make a wise choice.

Fifth, we believed that the option programs should not be so rigid that a student is prevented from substituting, when his reasons are sound, certain courses in the options for other courses.

The above general considerations were employed in the development of specific programs as follows:

Chemical engineering science option. Throughout the country a strong trend has developed toward a chemical

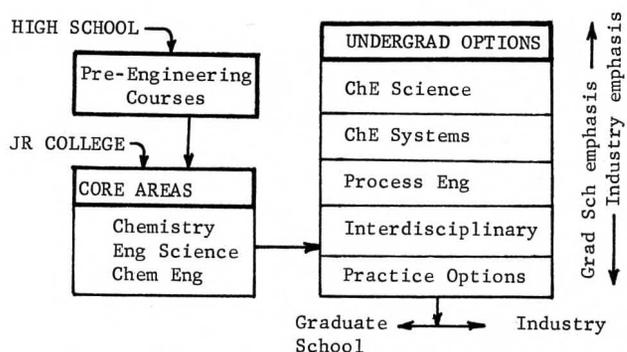


Figure 1. Flow Sheet for Undergraduate Options.

. . . we developed a curriculum that treated each student as an individual whose interests, talents, and career objectives could be expressed through a selection of option programs.

engineering science program that primarily prepares a student for graduate work and for a career in fundamental research and teaching. Although a large majority of our students go into industry we felt that our department should have such a science-oriented program available in order to provide (nevertheless) an alternative for the student who might otherwise go into the engineering science program available in the College of Engineering. We call this program our *chemical engineering science option*.

Operations, business, and technical sales options. Many of our students obtain jobs in operations and eventually in middle management where theoretical and mathematical tools are not as much needed as by the researcher. Programs for such students were designed for industrial employment or further study in business, marketing, or law. These were called the *operations options* and *business options*. A modification is available for students interested in careers in *technical sales*.

TABLE 1 — CORE AREAS

| Engineering Core | Chemistry Core | Chemical Engineering Core |
|-----------------------------|---------------------------|---------------------------|
| Computer Model Formulation* | Organic Chemistry | Thermodynamics* |
| Intro. to Elec. Eng. | Organic Chem. Processing* | Transport Phenomena* |
| Statics | Physical Chemistry | Chemical Kinetics* |
| Strength of Materials | Instrumental Analysis* | Systems Analysis* |
| Materials of Engineering* | | Solid-Fluid Systems* |
| Engineering Statistics | | Control Theory* |
| | | Stagewise Separations* |
| | | Cost Estimation* |
| | | Process Design* |

*Taught in ChE department.

Process engineering option. Many students actually do not know what they want to do after graduation. As a result, chemical engineering curricula have traditionally attempted to produce a highly versatile chemical engineer—one that can easily start his career in any of many work assignments. We felt a program of this type should be retained. We called this option *process engineering* but upgraded it by the addition of transport phenomena, computer modeling and applied math courses.

Systems engineering option. The systems engineering approach is as much a part of chemical engineering as any other field of engineering, including that taught in systems engineering departments. Chemical engineers are bringing the fruits of automation to the process industries through the effective use of computers, mathematical models and processes, and advanced hardware to the design and operation of chemical complexes. Consequently we developed a computer-oriented *systems engineering option* in order to fill this need and also as an

TABLE 2A — SUBJECTS STUDIED IN APPLIED SCIENCE OPTIONS

| | Process Eng. | ChE Systems | ChE Science |
|----------------------------------|--------------|-------------|-------------|
| Reactor Dynamics and Design | * | * | * |
| Math Models in ChE | * | * | * |
| Technical Electives | * | * | * |
| Process Optimization | | * | |
| Applied Molecular Theory | | | * |
| Advanced Process Design | * | | |
| Ind. and Systems Eng. | | * | |
| Applied Math Electives | | | * |
| Polymeric Materials | * | | |
| Process Economics | * | * | |
| Tensor Fields and Fluid Dynamics | | | * |
| Quarter Credits in Option | 22 | 22 | 22 |

alternative to the student who might otherwise enroll in the systems engineering program taught in the College of Engineering.

Interdisciplinary options. Some students have a difficult time choosing between chemical engineering and a "glamorous" field such as aerospace or nuclear engineering. At the same time the challenging problems of today tend to be coupled interactions between the application of engineering principles and the socio-economic needs of our society; e.g., pollution abatement, food production and/or population control. The inter-disciplinary options permit the chemical engineer with paralleled interests in other fields to take his degree in chemical engineering while at the same time studying 22 hours of approved courses in related disciplines such as aerospace engineering, environmental engineering, nuclear engineering, food science, or biomedical engineering. The latter program is approved for direct entrance into medical school.

Humanities or Liberal Studies. Many students today are concerned about the social problems of our society, about man's obligation to his fellow man and himself,

TABLE 2B — INTERDISCIPLINARY OPTIONS

| | |
|---|--|
| Chem-Aerospace Propulsion Aerodynamics | Chem-Biomedical Zoology Biology |
| Chem-Electrical Electronics Control Systems | Chem-Environmental Waste Treatment Special Topics |
| Chem-Food Science Chem. Principles Eng. Principles | Chem-Materials Elect. Properties Corrosion |
| Chem-Mechanical Turbines and Jets Refrigeration | Chem-Nuclear Nuclear Tech. Nuclear Chemistry |

TABLE 2C — PRACTICE OPTIONS

| Operations | Business & Sales | Humanities, or Liberal Studies |
|--|--|---|
| Corrosion or Electrochemical Engrg | Report Writing Speech Courses Management | Political Science Sociology History |
| Polymeric Materials Management | Electives Marketing Electives | English Philosophy Religion |
| Electives Process Economics ChE Electives | Process Economics ChE Electives | Foreign Languages Process Economics ChE Electives |

about values and ethics, and about the meaning of life itself. Therefore we developed a group of courses in the humanities and social sciences that would permit an engineering student to obtain a degree that was perhaps, because of its science content, more of a "liberal studies" program than that offered in the College of Art and Sciences.

GRADUATE PROGRAMS IN SCIENCE AND SYSTEMS

While some graduate students intend to teach and do basic research, many others are interested in industrial careers in development and design. Consequently the graduate program in the department was divided into three main areas:

(1) **Chemical Engineering Science:** transport phenomena, fluid dynamics, thermodynamics, kinetics, microstructure of matter, and materials science; (2) **Chemical Engineering Systems:** chemical reaction engineering, process control, process dynamics, optimization, separations processes; and (3) **Interdisciplinary Chemical Engineering:** energy conversion and fuel cells, polymer science, microelectronics, process economics, and bioengineering.

Master of Engineering with Project

There are four graduate programs in the department. These are: 1) the 45 quarter-hour Master of Science in Engineering program with thesis; 2) the 50 quarter-hour Master of Engineering pre-PhD program; 3) the 50 quarter-hour Master of Engineering terminal program with a project (which can involve a design, a cost analysis, an experimental investigation, a computer study, or a technical report); 4) the PhD program. Transfer between programs is possible within limits.

PhD Program Requires Research Proposal

This program includes a **written examination** (which may be waived), see below, a research

proposal defended orally, an **oral examination**, and a **final examination**. The research proposal sets forth and describes an original research problem and/or solution, which if carried through, would represent a significant contribution to chemical engineering knowledge. The area of the proposal may be the student's dissertation subject *only* if he has taken the written examination.

Graduate Courses

An orientation examination is used to determine whether entering students require any preliminary course work, before taking the six required core courses. After three to five quarters in residence, all Master of Engineering students and nearly all PhD students are required to take a written examination based on these core courses:

Models and Methods

Multidimensional and Discrete Systems
Thermodynamics of Reaction and Phase Equilibria
Fundamental Transport Phenomena
Process Dynamics 1 or Process Dynamics 2
Reactor Design and Optimization (Systems Program) or
Chemical Kinetics (Science Program)

During 1968 the following *additional* courses were taught by department faculty:

Mathematical Methods in Chemical Engineering
Applied Field Theory
Computer Control of Processes
Optimization Techniques
Transport Properties and Irreversible Thermodynamics
Applied Statistical Mechanics
Statistical Thermodynamics
Interfacial Transport Phenomena
Rheology
Non-Newtonian Fluid Dynamics
Chemical Energy Conversion
Particulate Systems
Applied Fluid Dynamics
Process Engineering
Process Equipment Design
Process and Plant Design
Process Economy Analysis
Tensor Fields and Fluid Dynamics
Analytical Techniques for Eng and Scientists 1
Analytical Techniques for Eng and Scientists 2
Analytical Techniques for Eng and Scientists 3

RESULTS

Student reaction to these diversified programs has been very good at both the undergraduate and graduate levels.

THE GATORS GO

(Continued from page 152)

"CENTER-OF-EXCELLENCE" GRANT

In August 1965, the University of Florida was awarded a 4.2 million dollar Science Development Grant by the National Science Foundation. The Chemical Engineering Department was among the seven participating departments in the University. The proposal submitted by the University was entitled "Radiation, Kinetics, and the Microstructure of Matter." The proposal stated that the first objective of the College of Engineering was "to improve the scientific base of education and research through increased emphasis on the engineering implications of the microstructure of matter." It pointed especially to the developing technology of microelectronics as "only one aspect of the very general field of microengineering which aims to place a strong emphasis upon the microscopic statistical view of nature and to relate this to human needs."

In keeping with this philosophy, the department defined and delineated the meaning of the phrase "microstructure of matter" from the standpoint of modern fundamental research in chemical engineering in terms of the following connotations:

1. **MOLECULAR.** This approach involves the use of a knowledge of statistical mechanics, molecular structure, and molecular and kinetic theory (a) to predict rates of chemical reaction either on catalyst surfaces or in homogeneous systems, (b) to predict adsorption rates, (c) to predict thermodynamic properties and phase equilibria, or (d) to predict transport properties such as diffusivity, thermal conductivity, or viscosity.

2. **PARTICULATE.** This approach analyzes particulate systems in terms of their statistical properties and the particle-continuum interaction. Such systems are found in industrial crystallizers and also include aerosols, mists, dispersions, and suspensions.

3. **STATISTICAL.** This approach is used to describe turbulent transport processes for energy, mass, and momentum in terms of elements in which fluctuations of velocity and other properties occur.

4. **CONTINUUM.** The microscopic view of matter can be thought of in terms of processes that occur at a point in a continuum. The conservation laws for energy, mass, and momentum can be expressed in terms of the differential equations of change.

Knowledge of matter from these microscopic points of view of course can be used in a given engineering system to predict macroscopic quantities such as the total energy or mass transport or the total friction or drag in a system. This

information can be incorporated with modern design and optimization techniques in the design of an engineering system or a complete plant.

NEW BUILDING FOR DEPARTMENT

In the fall of 1967 the department was able to move into a modern air-conditioned educational building containing 51,000 sq. ft. of research and teaching facilities made possible by a State bond issue and funds from the NSF grant. We now have undergraduate teaching space for modern laboratories in process measurements, transport properties, instrumental process analysis, unit operations, process transients and control theory, chemical reaction kinetics, and individual special projects. Graduate research space is available in process dynamics and computer control, transport phenomena and properties, *in vivo* transport studies, fluid dynamics and rheology.

COMPUTER CONTROLLED LABORATORY

Modern computer facilities will permit one to control any of several pieces of process equipment in the unit operations laboratory. At present, a distillation column is being tied to a remote IBM 1070 process control terminal which connects to the IBM 360/65 campus computer via telephone lines. We have designed and are building a special interface between the process equipment and the terminal which serves two major functions. First of all it is a patch panel permitting any one of several processes to be "patched" into the terminal using special jacks and plugs. Its second function results from the fact that one can simulate most of the computer actions to the process and all of the process responses to the computer at the interface itself. One can thus almost completely "debug" the computer software without the process and to some extent "debug" the process hookup without the computer.

The remote computer terminal with interface can tie to 40 analog inputs (low and high level), 30 digital inputs, 24 digital outputs, 10 pulse motor outputs (which can operate in parallel), a digital display, and a rotary switch input station. The terminal's transmission rate is 66 characters per second to and from the computer which will permit about 4 random accesses per second or about 20 analog to 60 digital sequential accesses per second.

The software is written in Fortran and is

quite modular permitting most of the essential portions to be used in all processes. The department also has two remote consoles for the IBM 360, a 60-amplifier Ease computer, and a WANG Calculator.

OTHER ACCOMPLISHMENTS

During the past three years, three different members of the faculty have won undergraduate teaching awards; Professor Tyner, Professor Gubbins, and Professor O'Connell. This year the Sigma Xi research award went to a chemical engineering graduate student and the Phi Kappa Phi award for the outstanding student in the University went to a chemical engineering junior. Last year the faculty published 20 papers, had 14 others accepted, and submitted 14. Two books were published, two accepted and two submitted.

CONCLUSION

If the goal of the department is an excellence that is not measured by quantitative indices, the above achievements are not in themselves sufficient indication that excellence has been attained. But they may indicate that the seeds of excellence have indeed been planted and have germinated. If these are now nurtured by additional support, the progress of the department toward excellence can continue — not only in its research program, not only in its instructional program, not only in the achievement of each of its multiple objectives, but also in the fulfillment of its ultimate aim: the betterment of human society.

(Cont'd from p. 140)

OPTIMIZATION: R. R. Hughes

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CHEMICAL ENGINEERING DIVISION ACTIVITIES

Seventh Annual Lectureship Award to C. J. Pings

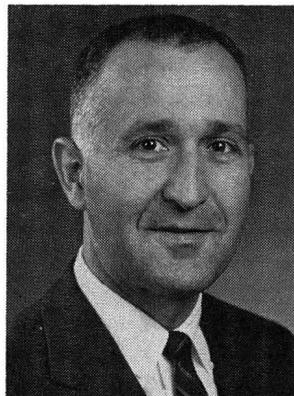
The 1969 ASEE Chemical Engineering Division Lecturer is Dr. C. J. Pings of the California Institute of Technology. The purpose of this award lecture is to recognize and encourage outstanding achievement in an important field of fundamental chemical engineering theory or practice. *The 3M Company provides the financial support for this annual lecture award.*

Bestowed annually upon a distinguished engineering educator who delivers the Annual Lecture of the Chemical Engineering Division, the award consists of \$1,000 and an engraved certificate. These were presented to this year's Lecturer, Dr. C. J. Pings, at the Annual Chemical Engineering Division Banquet held June 24, 1969 at the Pennsylvania State University. Dr. Pings spoke on "A Chemical Engineer Looks at the Physics of Simple Liquids." A paper based upon his lecture will be published in an early issue of **Chemical Engineering Education**.

PREVIOUS LECTURES

- 1963, A. B. Metzner, University of Delaware, "Non-Newtonian fluids."
- 1964, C. R. Wilke, University of California, "Mass transfer in turbulent flow."
- 1965, Leon Lapidus, Princeton University, "Aspects of modern control theory and application."
- 1966, Octave Levenspiel, Illinois Institute of Technology, "Changing Attitudes to Reactor Design."
- 1967, Andreas Acrivos, Stanford University, "Matched Asymptotic Expansions."
- 1968, L. E. Scriven, University of Minnesota, "Flow and Transfer at Fluid Interfaces."

BIOGRAPHIC SKETCH



Cornelius J. Pings was born in Montana in 1929 and entered the California Institute of Technology in 1947 from which he received a BS degree in Applied Chemistry in 1951, an MS degree in Chemical Engineering in 1952, and a PhD degree in Chemical Engineering in 1955. He served on the faculty at Stanford University from 1955 to 1959 before returning to Caltech where he is now

Professor of Chemical Engineering.

In research and scholarly activities his interests have centered about the areas of applied chemical thermodynamics and the physics and chemistry of liquids. In the area of thermodynamics his work has led to important improvements in the methods for quantitatively describing the displacement of chemical equilibria. His research in liquid state physics and chemistry, which has been both theoretical and experimental, has the long-range objective of fundamental elucidation of the liquid state. He has developed one of the most extensive and best equipped laboratories in the United States for the fundamental study of fluids. Recent advances, deal with sound absorption at critical states, the structure of liquid argon, and studies of intermolecular forces.

In addition to his research and teaching activities, he has been active in faculty government and in student affairs. He has served for the past year as chairman of a special faculty committee on the aims and goals of Caltech. Also active in civic affairs, Dr. Pings was named in 1968 to the Community Redevelopment Agency of the City of Pasadena. He has served as a consultant to a number of industrial firms and to the Department of Defense.

Professor Pings served as Visiting Professor of Chemical Engineering at the University of Brazil in 1963. He has received two Presentation Awards from the AIChE—one from the 56th National Meeting in Houston (1963) and the other from the 56th Annual Meeting in San Francisco (1965). He is editor of the *Journal of Physics and Chemistry of Liquids*, and will serve in August 1969, as Chairman of the Gordon Research Conference on the Chemistry and Physics of Liquids.

The graphic consists of three rows of white-outlined blocks on a black background. The top row has two blocks with the letters 'D' and 'E'. The middle row has four blocks with the letters 'V', 'E', 'L', and 'O'. The bottom row has six blocks with the letters 'P', 'M', 'E', 'N', 'T'. To the left of the 'P' block is the 'RJR' logo, which consists of the letters 'RJR' in a bold, sans-serif font inside a white oval.

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